Neutrino Physics at Kamioka

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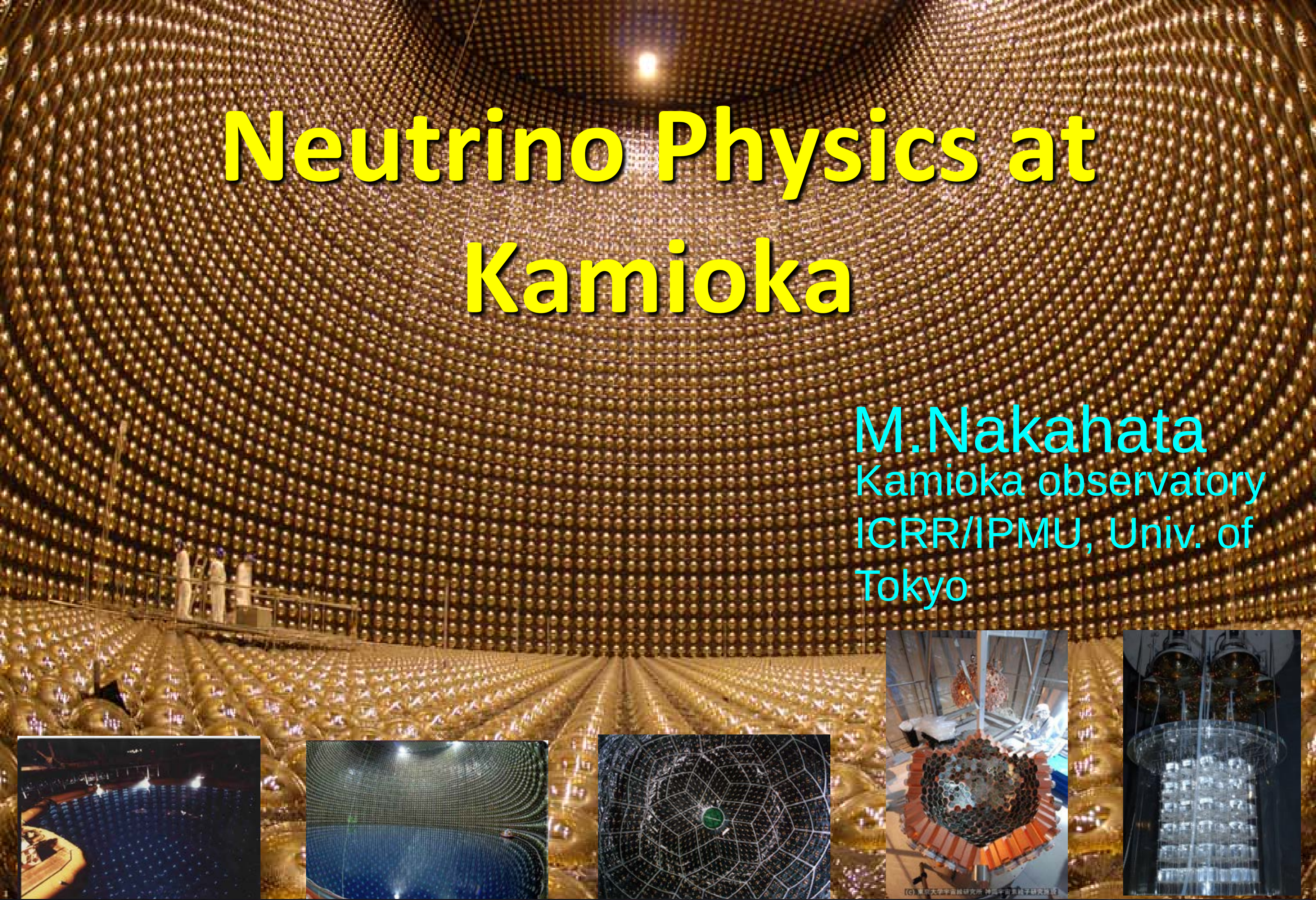
Kamioka observatory
ICRR/IPMU, Univ. of Tokyo

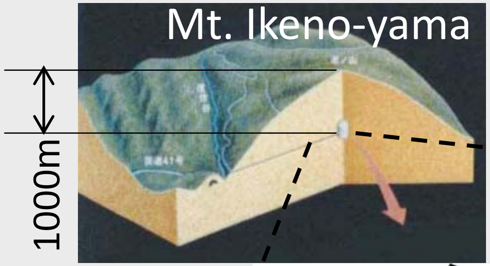


IBS Conference on Dark World

Contents

- Current experiments at Kamioka
- Brief history of neutrino experiments at Kamioka
- Neutrino oscillations
  - What we know now
  - What we don't know yet
- Recent highlights from Super-K and T2K
- Future at Super-K, and Hyper-K project

Kamioka underground experiments (NOW)

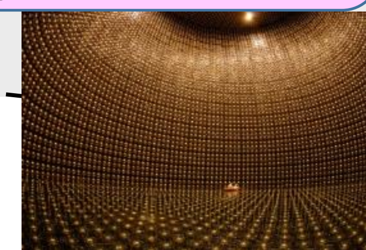


KamLAND (Tohoku Univ.)

1000ton liquid scintillator detector
Reactor, geo neutrinos
^{136}Xe double beta decay

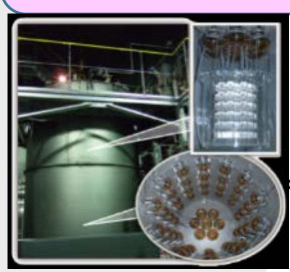
Super-Kamiokande

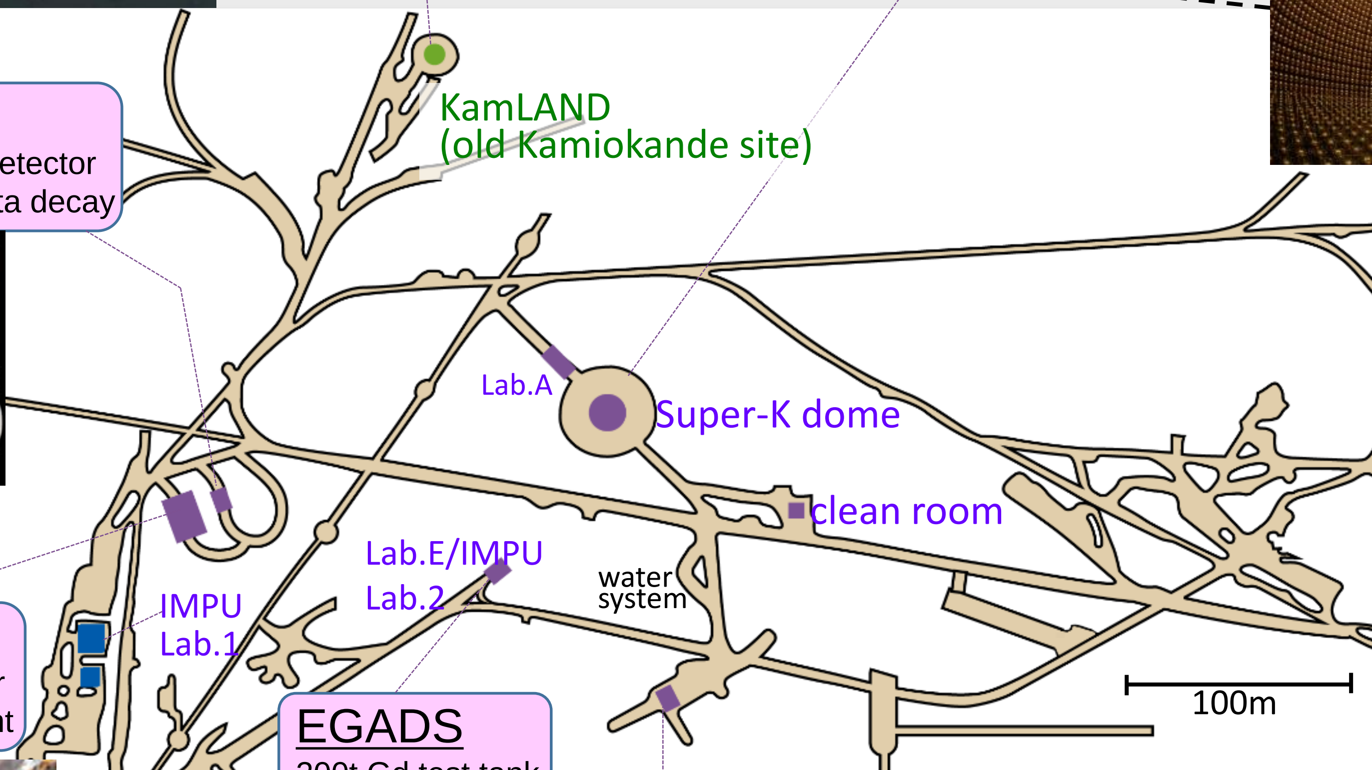
50,000 ton water Cherenkov detector
Atmospheric, solar, supernova neutrinos
proton decay, indirect dark matter search
Far detector for T2K



CANDLES

CaF_2 scintillation detector
for ^{48}Ca double beta decay





XMASS

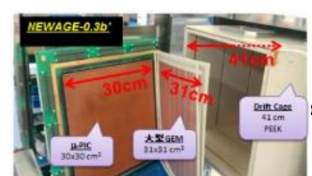
Direct dark matter search experiment

EGADS

200t Gd test tank

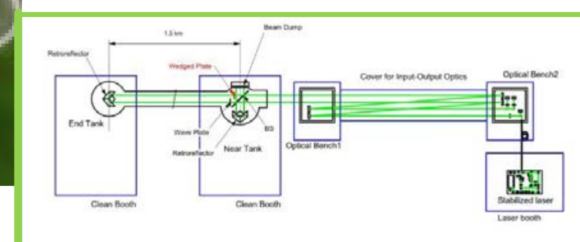
NEWAGE

Direction dark matter experiment

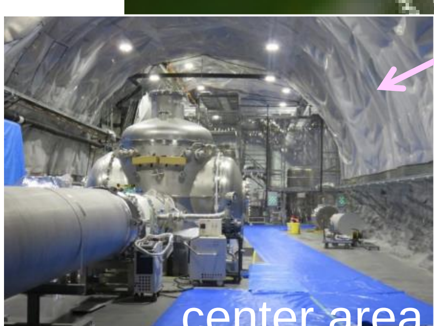


Kamioka underground experiments (NOW)

Laser strainmeter



1.5km Geophysics interferometer



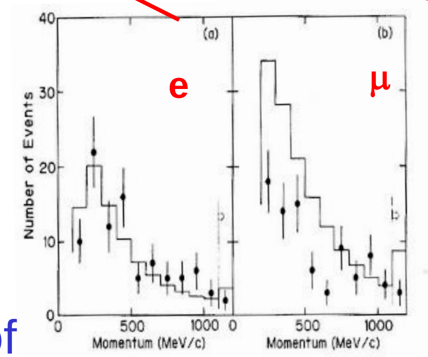
KAGRA
Gravitational-wave
Telescope
(under construction. Start in 2019)

Brief history of Kamioka underground

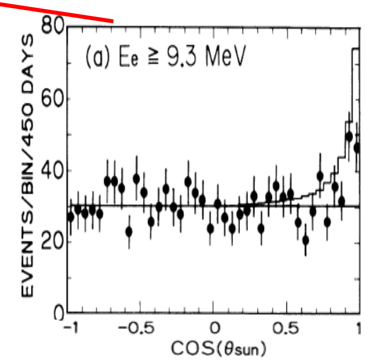
1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997

Kamiokande start (3,000t total vol.)

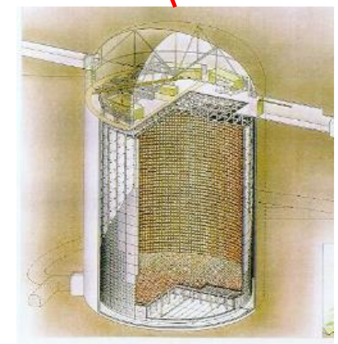
Observation of neutrinos from SN1987A



Atmospheric ν anomaly

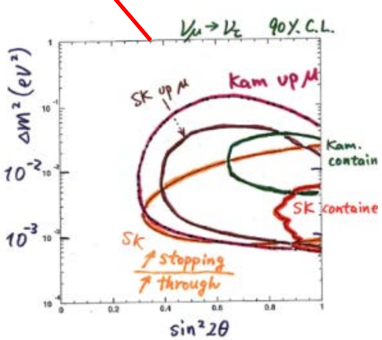


Solar ν measu-rement (by Kamiokande)

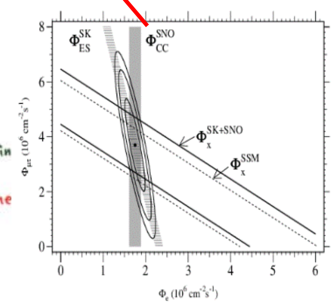


Super-K start (50,000 total vol.)

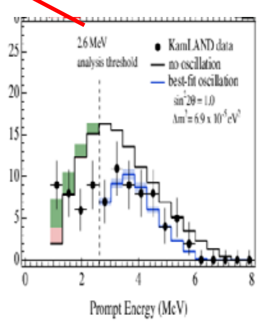
1998	1999	2000	2001	2002	2003	2004	……	…..	2011	2012	2013	2014	2015	2016



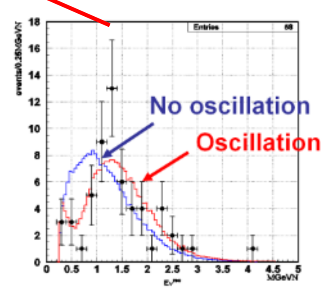
Discovery of atmospheric ν oscillation



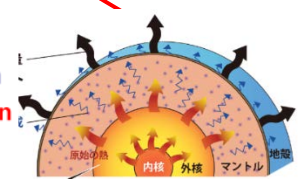
Discovery of solar ν osc. (SK vs. SNO CC)



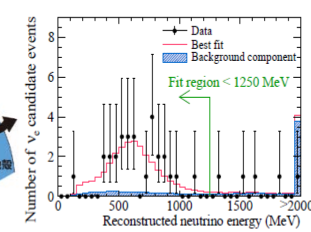
Discovery of reactor ν osc. （KamLAND）



Confirm osc. by artificial ν (K2K)



Discovery of geo-ν (KamLAND)



Discovery of ν_e appear-ance(T2K)

Neutrino oscillations

Weak interaction eigenstates →

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

← Mass eigenstates

PMNS(Pontecorvo-Maki-Nakagawa-Sakata) matrix

The general expression for the oscillation probability in vacuum is

$$P(\nu_\alpha \to \nu_\beta; L) = \delta_{\alpha\beta} - 4\sum_{j<k} \mathrm{Re}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}\right) \sin^2\left(\frac{\Delta E_{jk} L}{2}\right)$$
$$-2\sum_{j<k} \mathrm{Im}\left(U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k}\right) \sin\left(\Delta E_{jk} L\right),$$

where $\Delta E_{jk} \equiv \sqrt{m_j^2 + p^2} - \sqrt{m_k^2 + p^2} = \Delta m_{jk}^2 / 2E.$

m_i is the mass of i-th eigenstate, L is the length of travel, and E is the neutrino energy.

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Matrix

Weak interaction eigenstate $\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$ Mass eigenstate

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & +c_{23} & +s_{23} \\ 0 & -s_{23} & +c_{23} \end{pmatrix} \begin{pmatrix} +c_{13} & 0 & +s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & +c_{13} \end{pmatrix} \begin{pmatrix} +c_{12} & +s_{12} & 0 \\ -s_{12} & +c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{13}s_{23}e^{-i\delta} & c_{12}c_{23}-s_{12}s_{13}s_{23}e^{-i\delta} & c_{13}s_{23} \\ s_{12}s_{23}-c_{12}s_{13}c_{23}e^{-i\delta} & -c_{12}s_{23}-s_{12}s_{13}c_{23}e^{-i\delta} & c_{13}c_{23} \end{pmatrix}$$

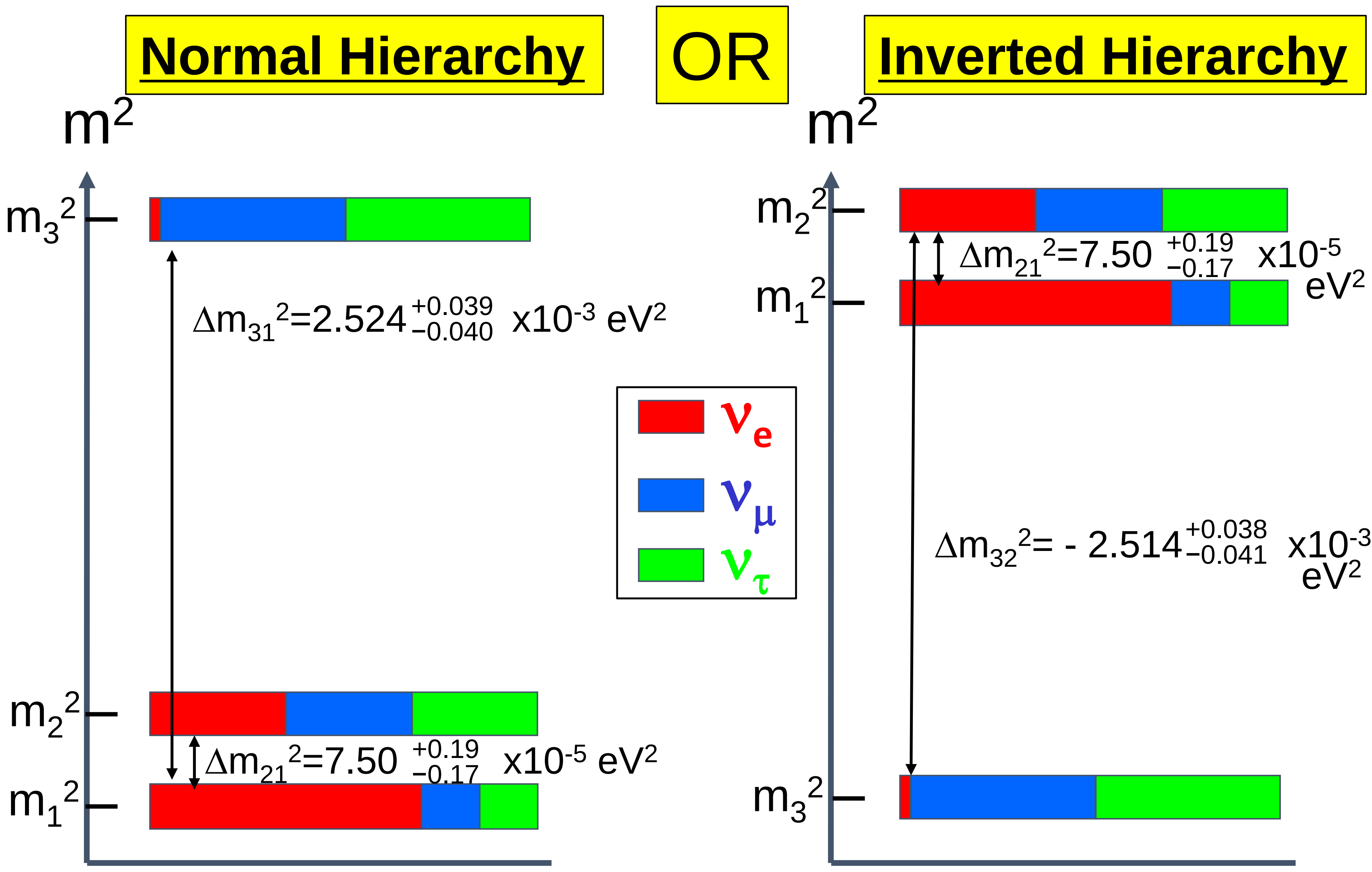
$s_{ij}=\sin\theta_{ij}$、$c_{ij}=\cos\theta_{ij}$

$\Delta m_{ij}^2 = m_i^2 - m_j^2$; Δm_{12}^2, Δm_{23}^2, Δm_{31}^2

δ : Dirac CP phase

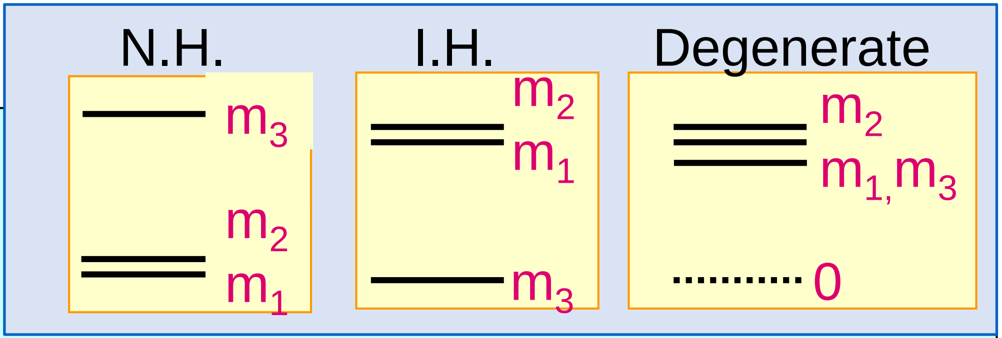
Majorana CP phase is not shown here because it does not affect neutrino oscillations.

Neutrino mass and mixing (what we know now)



Numbers from I. Esteban et al., JHEP 01 (2017) 087

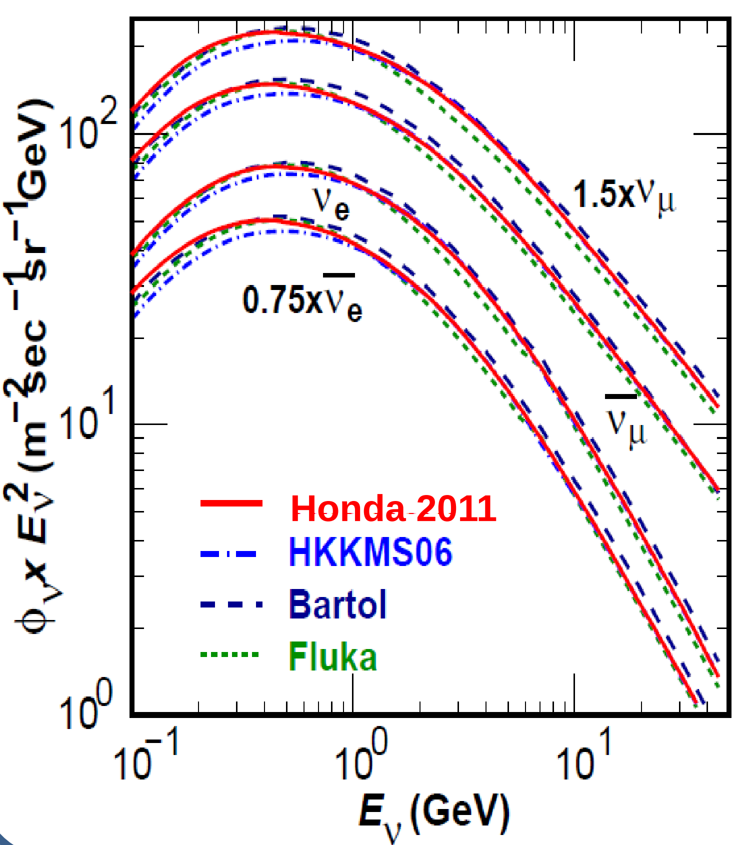
What we don't know yet



- Which mass hierarchy?
- Is CP phase δ finite?
- Is θ_{23} =45° >45° or <45° ?
- Absolute mass of neutrinos? (→ direct mass experiments, double beta decay experiments)
- Majorana or Dirac mass? (→ double beta decay experiments)
- Sterile neutrino (LSND anomaly)? (→ short baseline accelerator/reactor/source experiments)

Recent Highlights from SK and T2K

Atmospheric Neutrinos



Honda et al., Phys. Rev. D83, 123001 (2011).

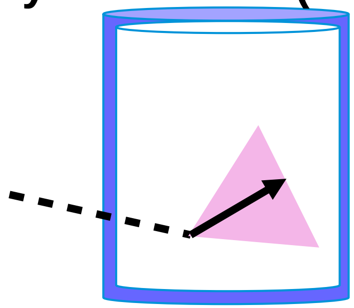
- Cosmic rays interact with air nuclei and the decay of pions and kaons produce neutrinos

$$P + A \rightarrow N + \pi^{\pm} + X$$
$$\hookrightarrow \mu^{\pm} + \overset{(-)}{\nu}_\mu$$
$$\hookrightarrow e^{\pm} + \overset{(-)}{\nu}_e + \overset{(-)}{\nu}_\mu$$

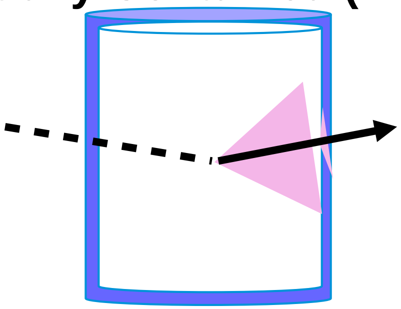
- νs travel 10 – 10,000 km before detection
- Both ν_μ and ν_e (ν_μ/ν_e = 2 at low energy)
- Both neutrinos and anti-neutrinos
  - ~ 30% of final analysis samples are antineutrinos
- Flux spans many decades in energy ~100 MeV – 100TeV
- Excellent tool for broad studies of neutrino oscillations

SK: Atmospheric ν Analysis Samples

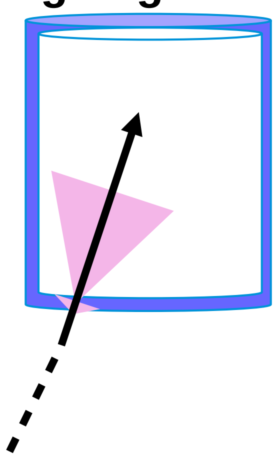
Fully Contained (FC)

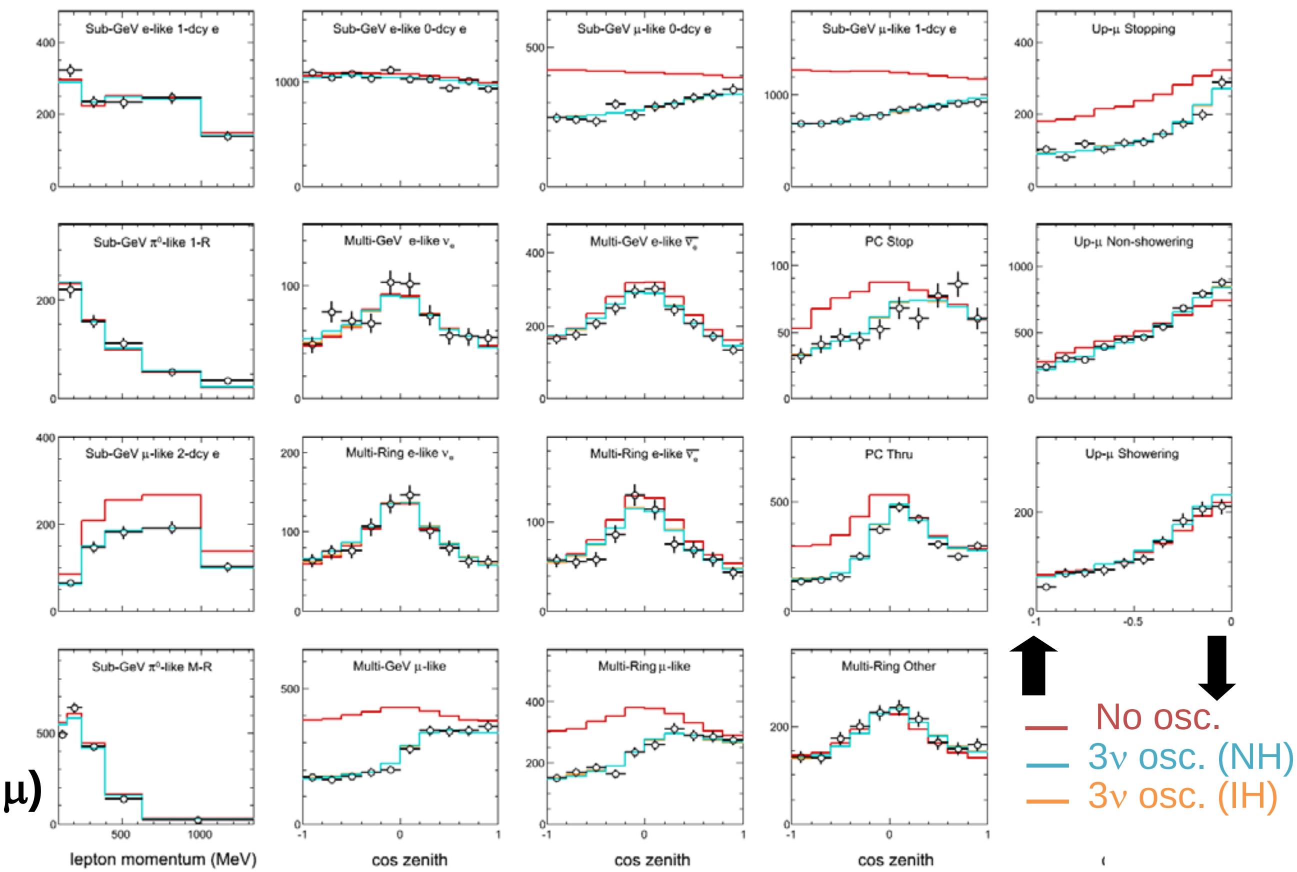


Partially Contained (PC)



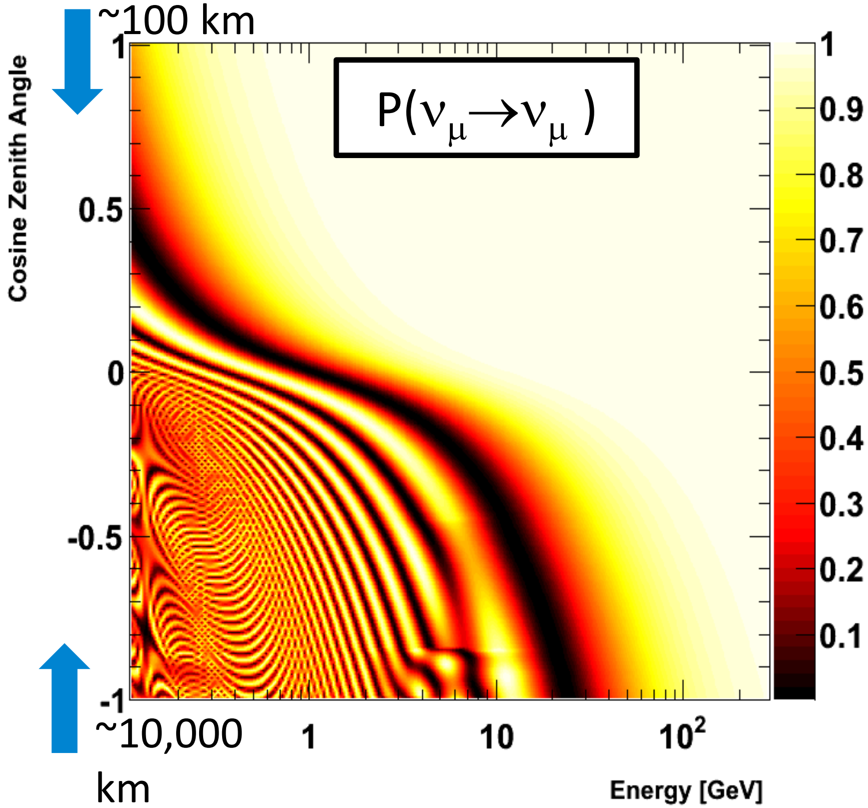
Upward-going Muons (Up-μ)

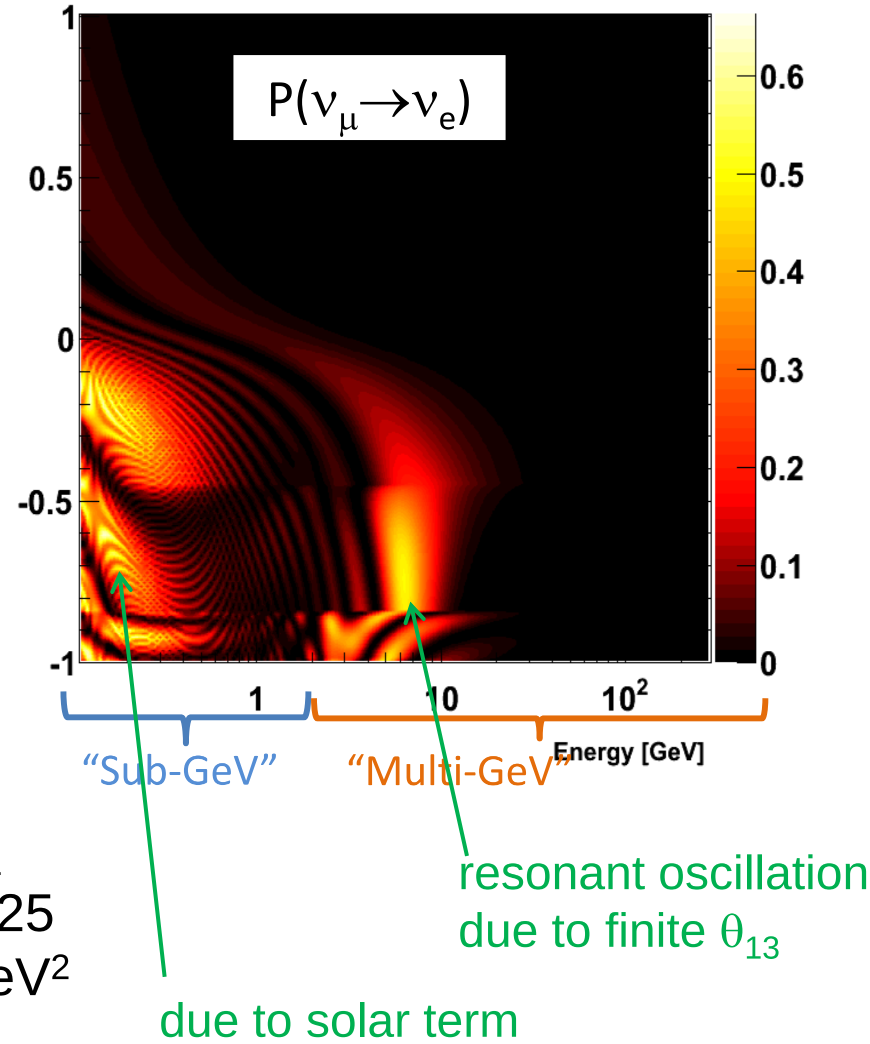




- **5,326 days** of atmospheric neutrino data (Through April 2016)
- **54,779 events** in total (43,476 FC, 3,367 PC, and 7,936 UP-μ)
- **19 analysis samples**: Sub-divided by event topology (FC/PC,UP-μ), energy range, e/μ–like, and # of rings. Multi-GeV e-like samples are divided into ν-like and $\bar{\nu}$–like samples in order to improve sensitivity for mass hierarchy.

Oscillation probability maps





Oscillation parameters used here are

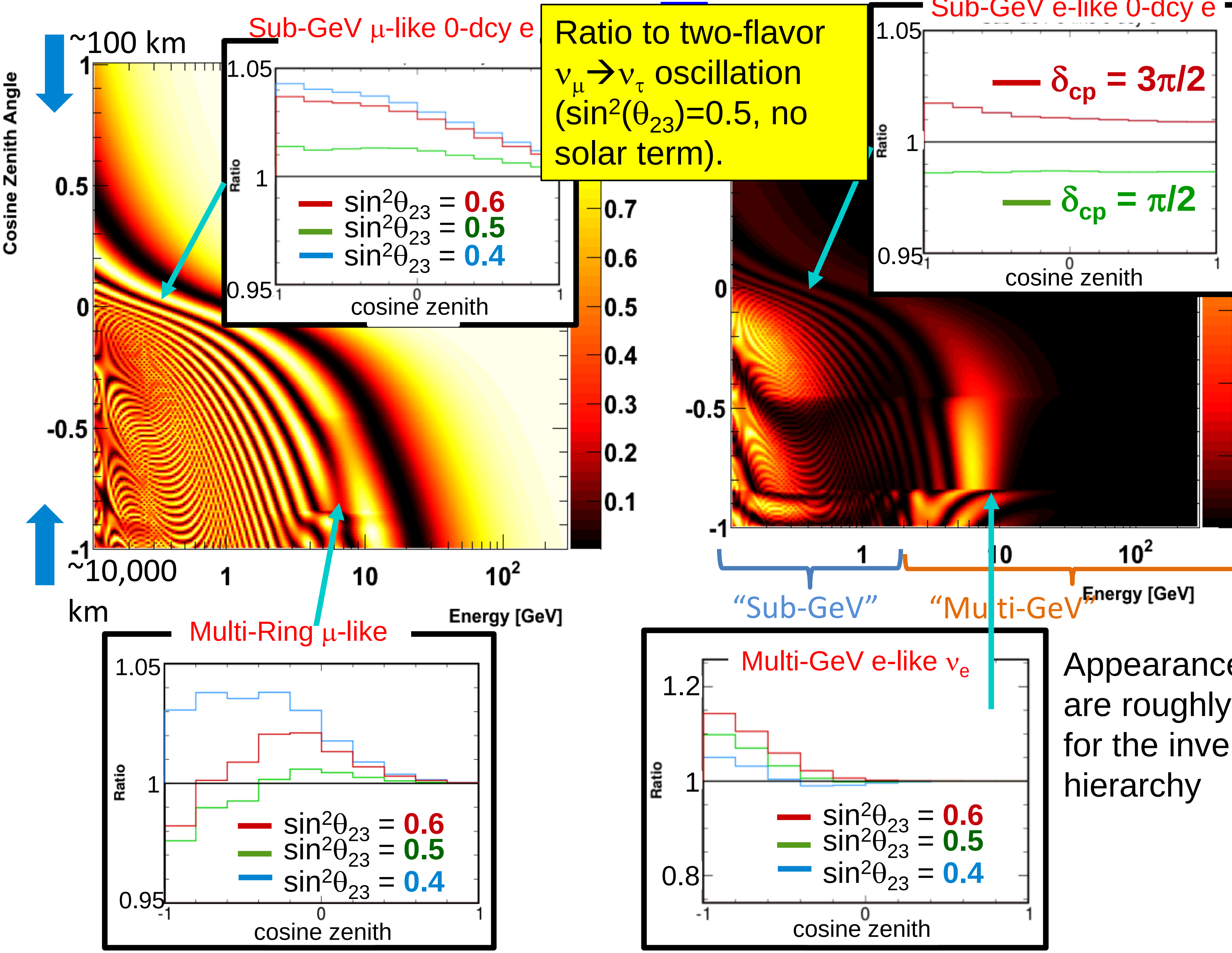
$\sin^2\theta_{12}=0.31$, $\sin^2\theta_{23}=0.5$, $\sin^2\theta_{13}=0.025$

$\Delta m^2_{12}=7.6\times10^{-5}$ eV^2, $\Delta m^2_{23}=2.5\times10^{-3}$ eV^2

Normal Hierarchy (NH)

$\delta CP=0.0$

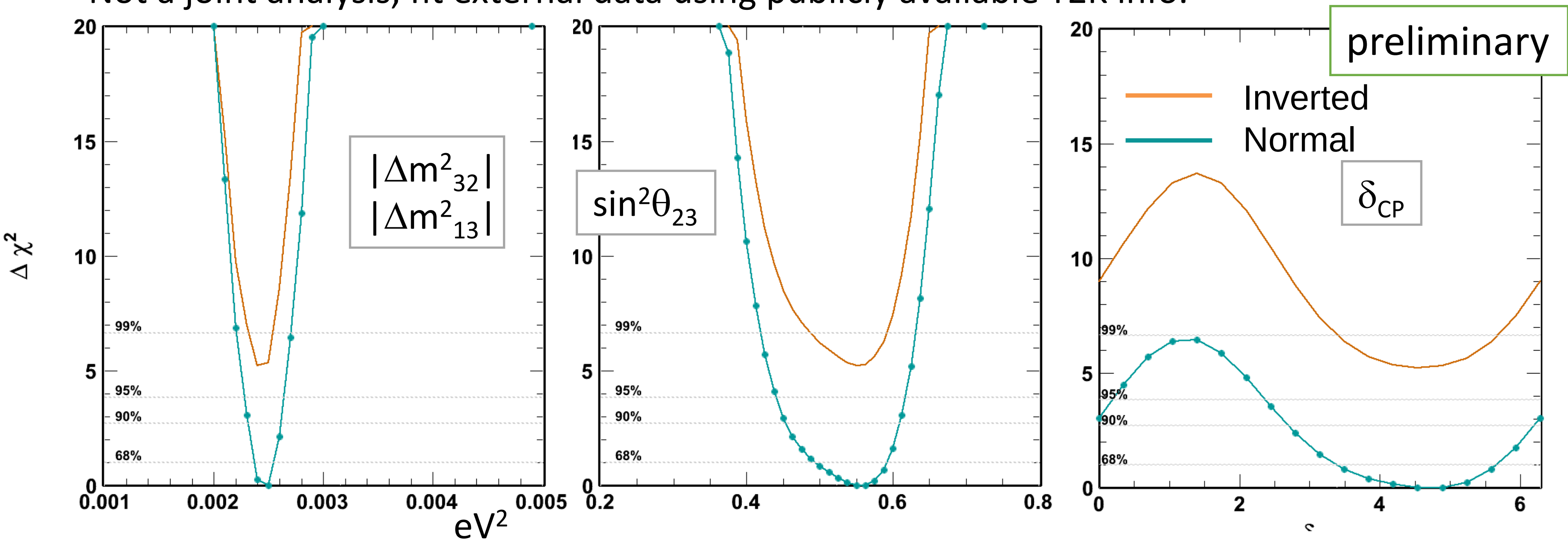
Effects of θ_{23} and δCP



Appearance effects are roughly halved for the inverted hierarchy

SK atmospheric ν analysis (with T2K constraint)

Not a joint analysis, fit external data using publicly available T2K info.



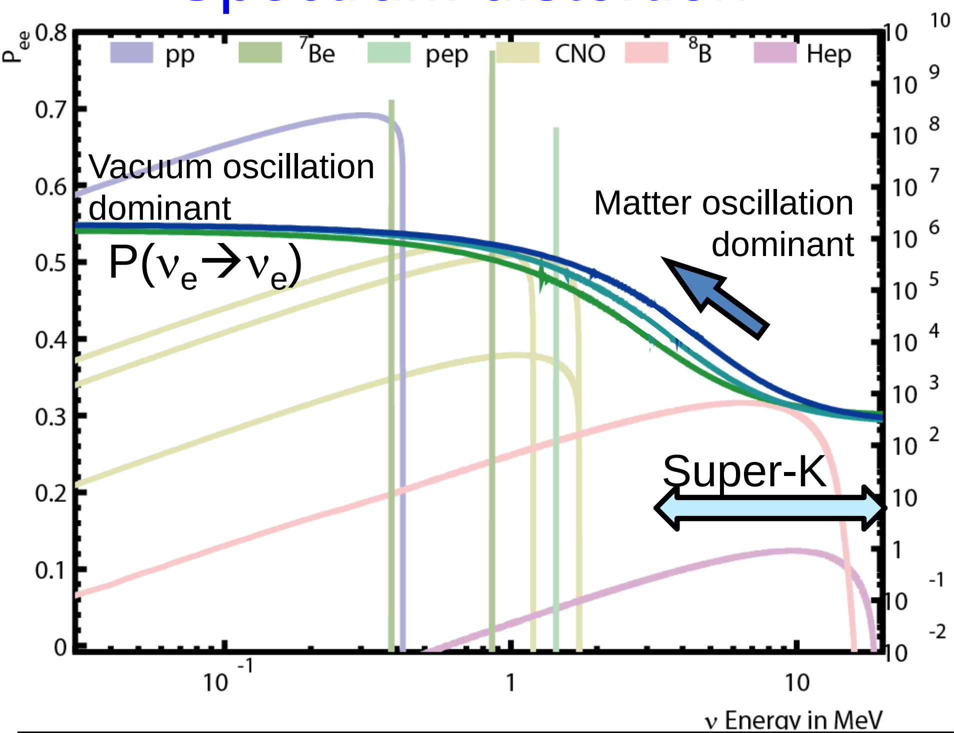
Fit (585 dof)	χ^2	$\sin^2\theta_{13}$	δ_{CP}	$\sin^2\theta_{23}$	$\|\Delta m^2_{32}\|$ eV^2
SK+T2K (IH)	644.82	0.0219 (fix)	4.538	0.55	2.5×10^{-3}
SK+T2K (NH)	639.61	0.0219 (fix)	4.887	0.55	2.4×10^{-3}

- SK+T2K (θ_{13} fixed): $\Delta\chi^2 = \chi^2_{NH}-\chi^2_{IH} = -5.2$
  (-3.8 exp. for SK best, -3.1 for combined best)
- Under IH hypothesis, the probability to obtain $\Delta\chi^2$ of -5.2 or less is 0.024 ($\sin^2\theta_{23}$=0.6) and 0.001 ($\sin^2\theta_{23}$=0.4).

SK: ^{8}B solar neutrino measurement

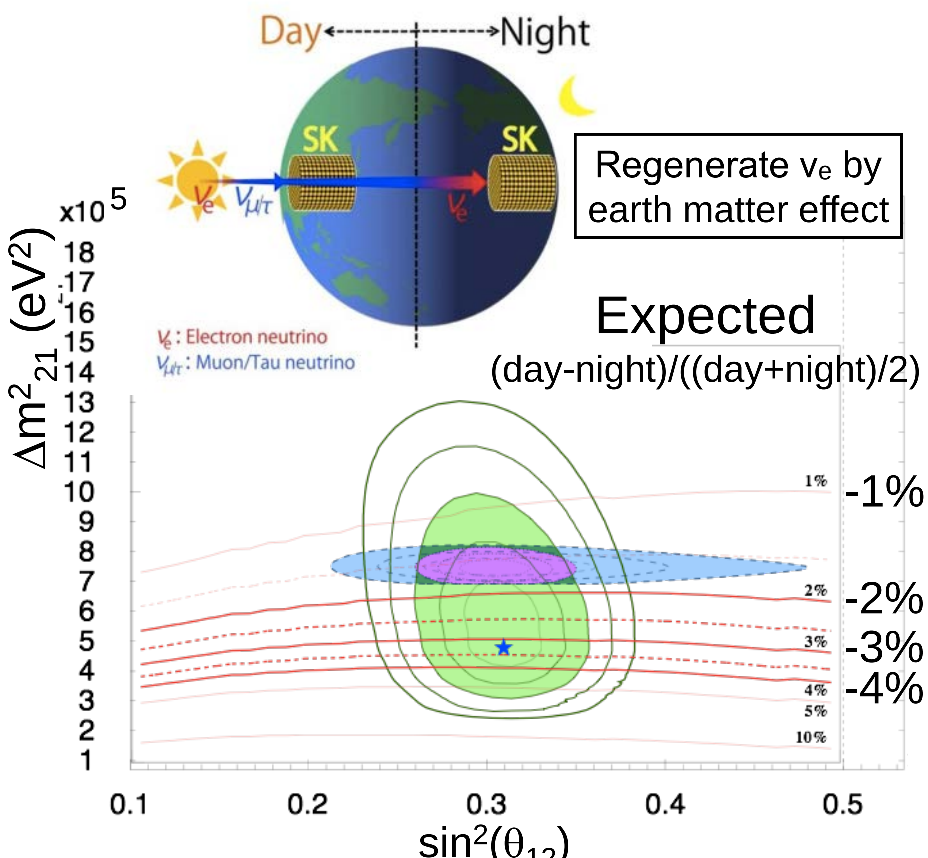
- High statistics (~20events/day) measurement of ^{8}B solar neutrinos
  - Possible time variation of the flux
  - Energy spectrum distortion due to solar matter effect
  - Day-night flux asymmetry due to earth matter effect

Spectrum distortion



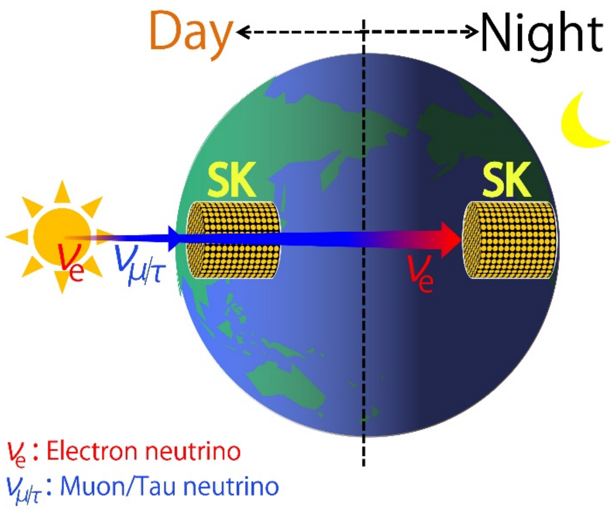
Super-K can search for the spectrum “upturn” expected by neutrino oscillation MSW effect

Day-Night flux asymmetry



SK solar ν: day/night effect

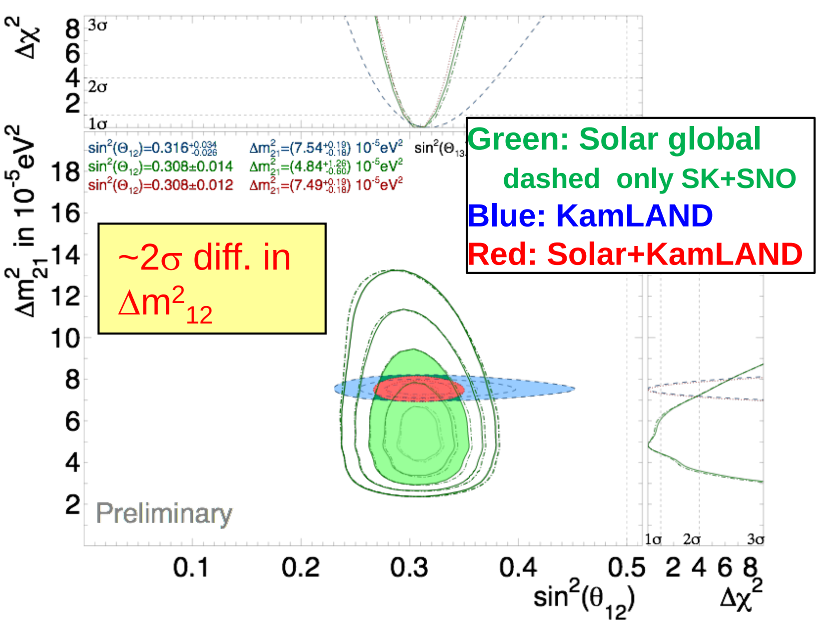
$$A_{DN} = \frac{(Day - Night)}{(Day + Night)/2}$$



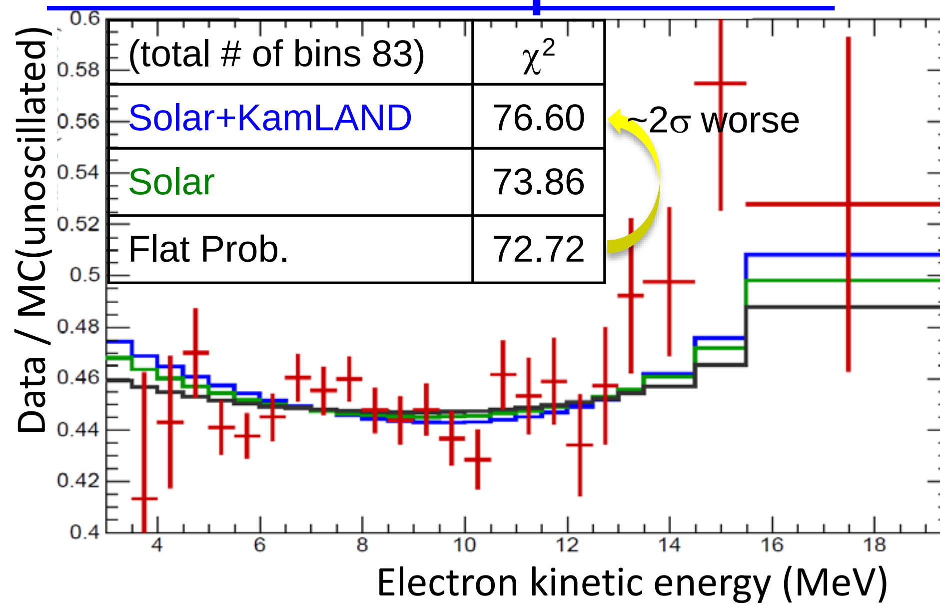
	D/N asymmetry (A_{DN})
	Δm^2_{21}=4.84x10^{-5} eV^2
SK-I	-2.0±1.8±1.0%
SK-II	-4.4±3.8±1.0%
SK-III	-4.2±2.7±0.7%
SK-IV	-3.6±1.6±0.6%
combined	-3.3±1.0±0.5%
non-zero significance	3.0σ

Direct indication of matter effect.

Solar global analysis



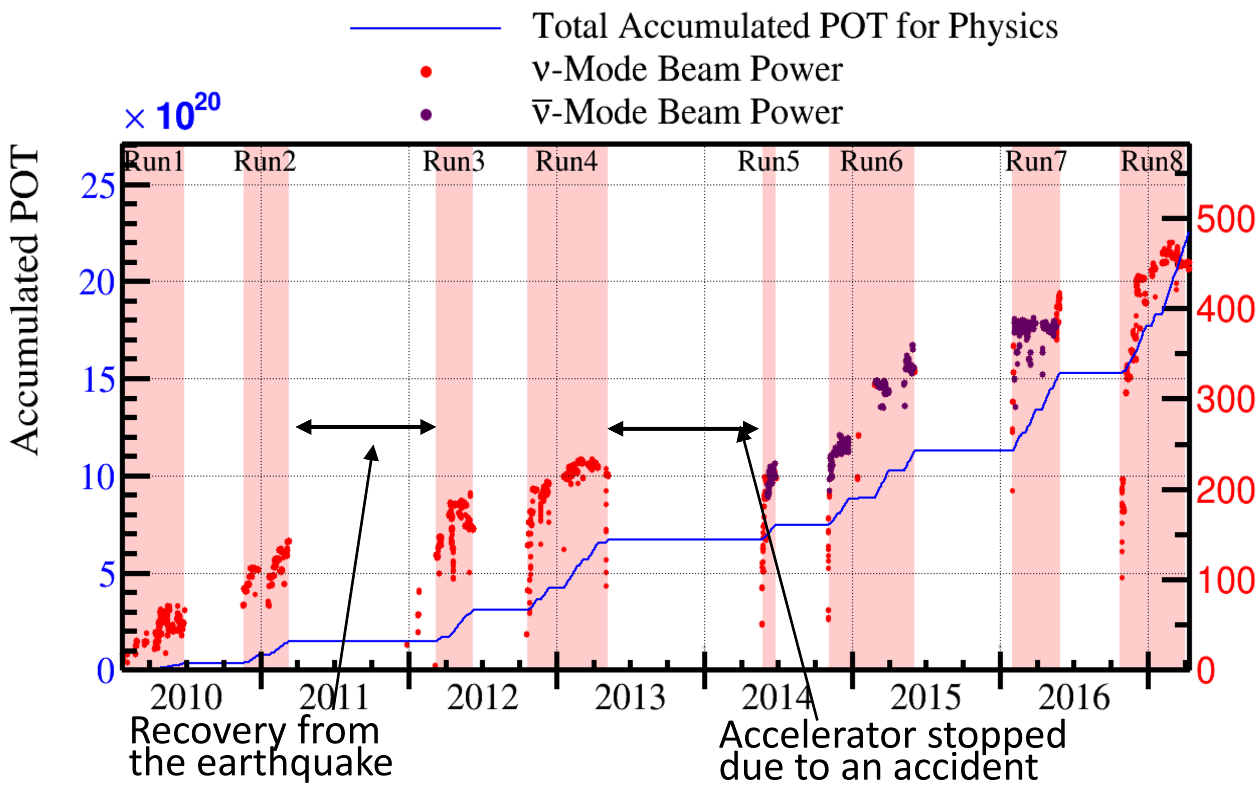
SK solar ν: spectrum



(total # of bins 83)	χ^2
Solar+KamLAND	76.60
Solar	73.86
Flat Prob.	72.72

Latest results from T2K

- ν_e appearance for the study of θ_{13} and δCP
- ν_μ disappearance for the study of θ_{23} & Δm^2_{23}



Until April 2017

22×10^{20} POT

(~28% of the planned total)

Neutrino mode

14.7×10^{20} POT

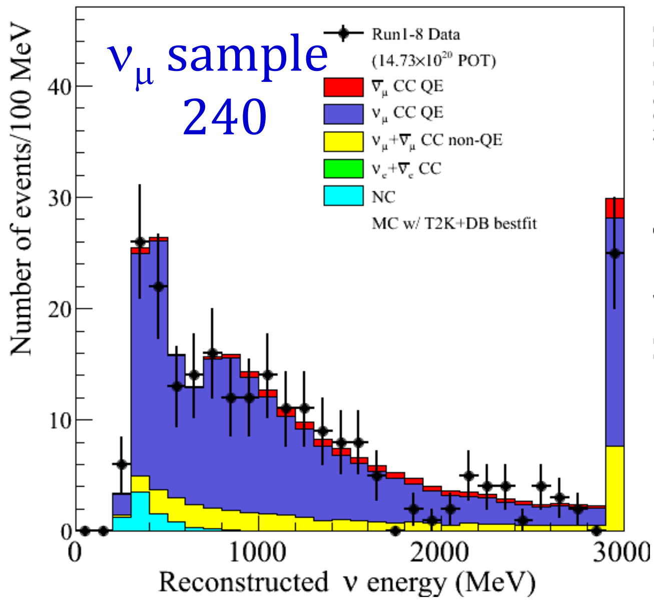
Anti-Neutrino mode

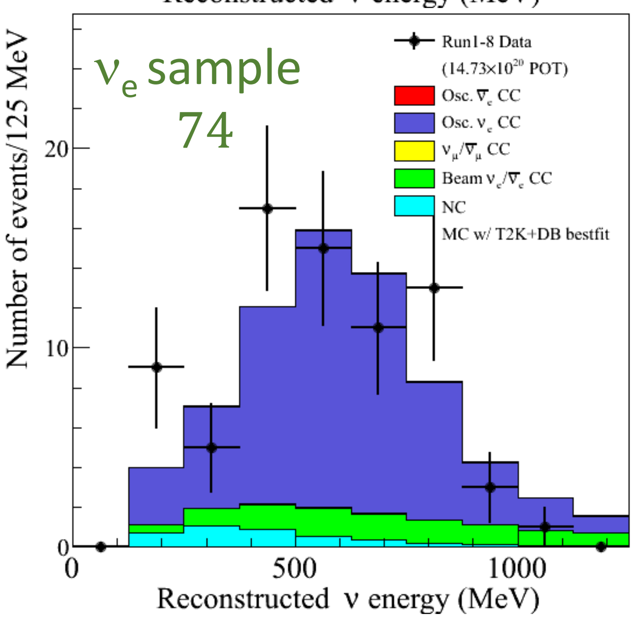
7.56×10^{20} POT

(POT: Proton On Target)

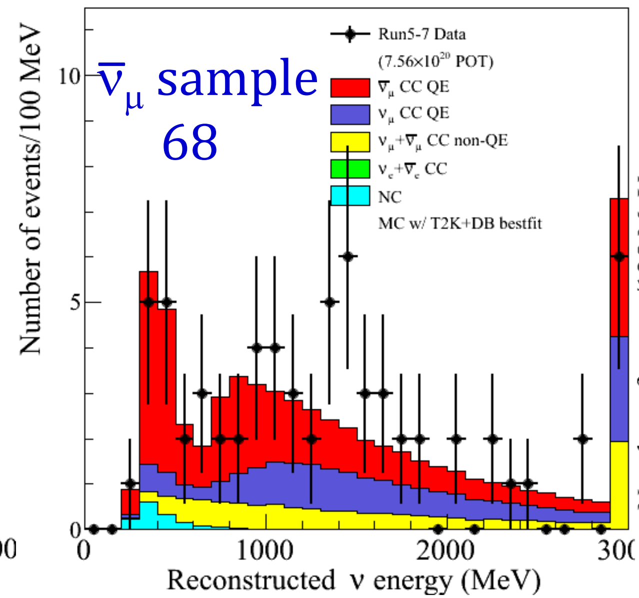
T2K: ν_μ disappearance and ν_e appearance data

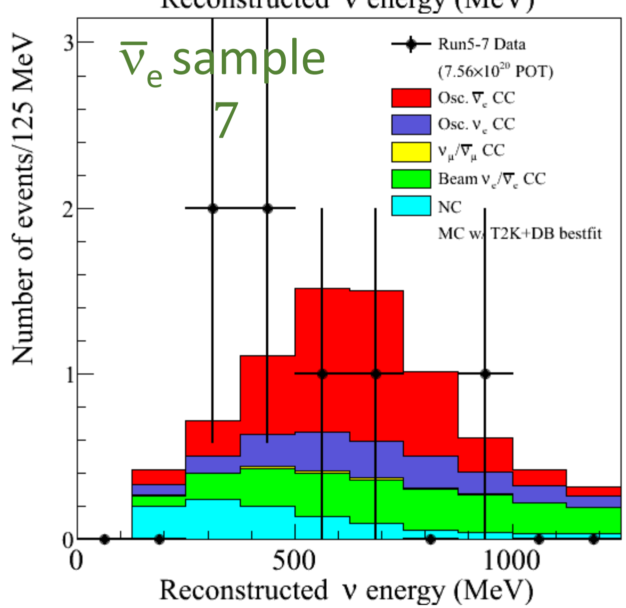
ν_μ 14.7x10^{20} POT





$\bar{\nu}_\mu$ 7.5x10^{20} POT

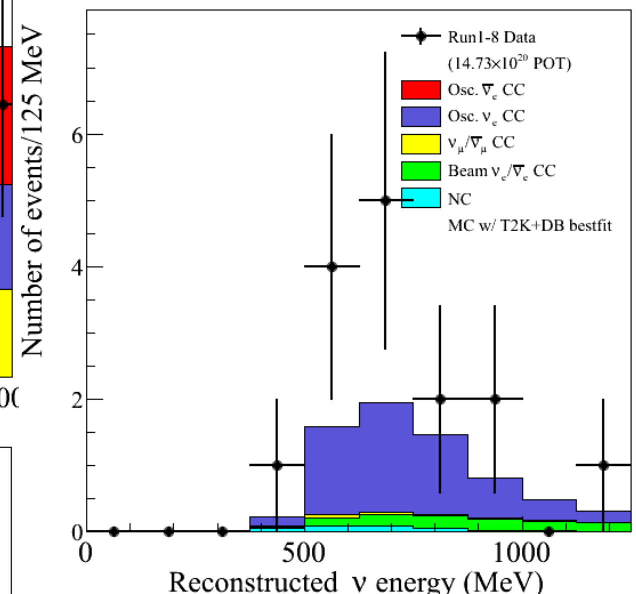




New category

ν_e (e^- + π^+) sample

15

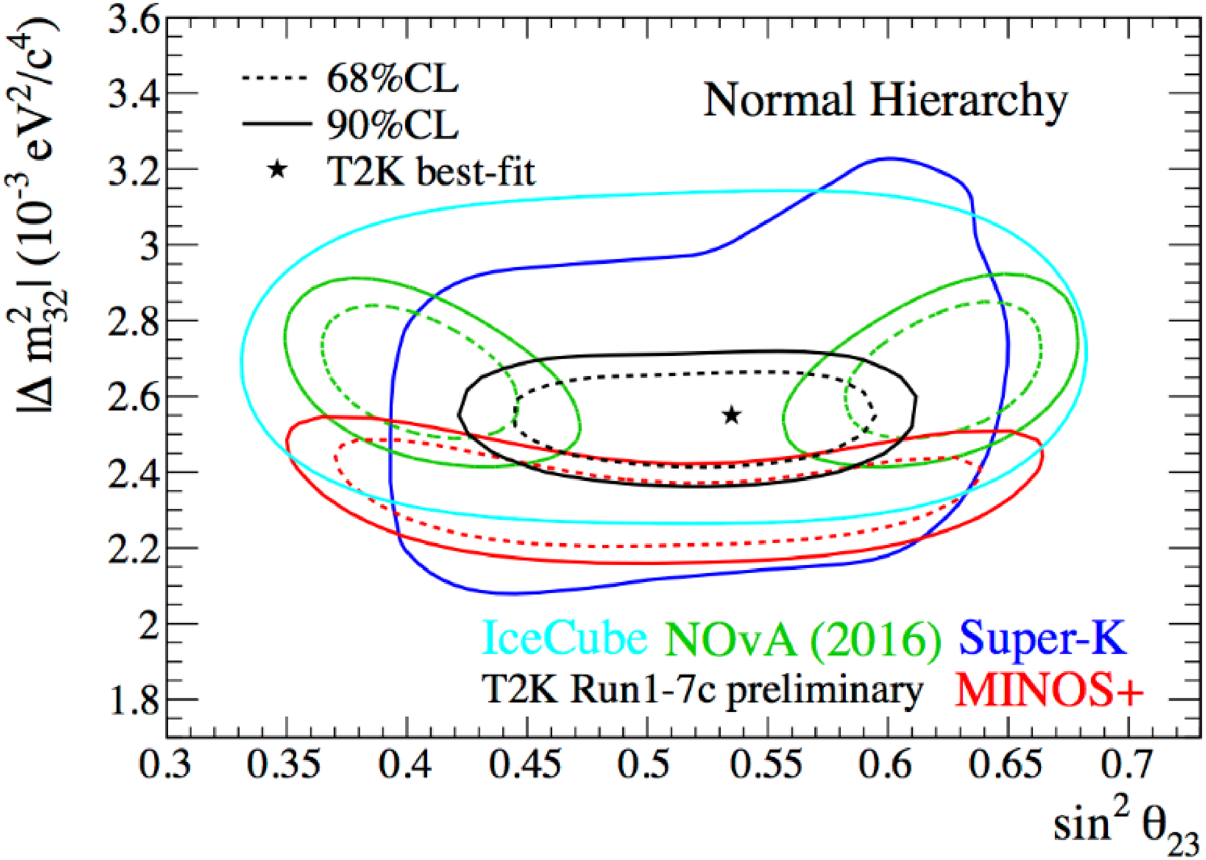


Parameter	Value
Δm^2_{21}	$7.53 \times 10^{-5}\, eV^2$
Δm^2_{23}	$2.509 \times 10^{-3}\, eV^2$
$\sin^2\theta_{12}$	0.304
$\sin^2\theta_{13}$	0.0217
$\sin^2\theta_{23}$	0.528
δ_{CP}	-1.601
Mass Hierarchy	Normal
ν Travel Length	295 km
Earth Density	2.6 g$\cdot$ cm^{-3}

T2K: results from $\nu_\mu+\bar{\nu}_\mu$ disappearance

ν_μ 7.57x10^{20} POT, $\bar{\nu}_\mu$ 7.53x10^{20} POT data

Oscillation parameters of $\sin^2\theta_{23}$ and Δm^2_{32} compared with others



Best fit values:

$(\sin^2(\theta_{23}), |\Delta m^2_{32}|)=$

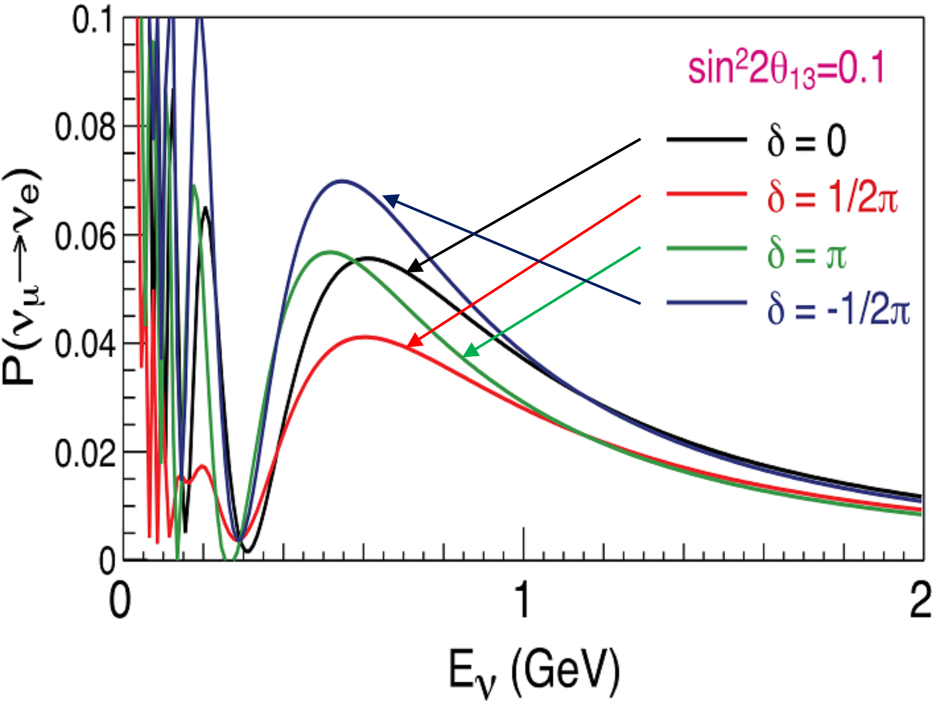
$(0.532, 2.545\times10^{-3}(\text{eV}^2))$

T2K has given the most previse measurement. T2K favors maximal mixing ($\sin^2\theta_{23}$=0.5) but NOvA disfavors. Need more data to conclude.

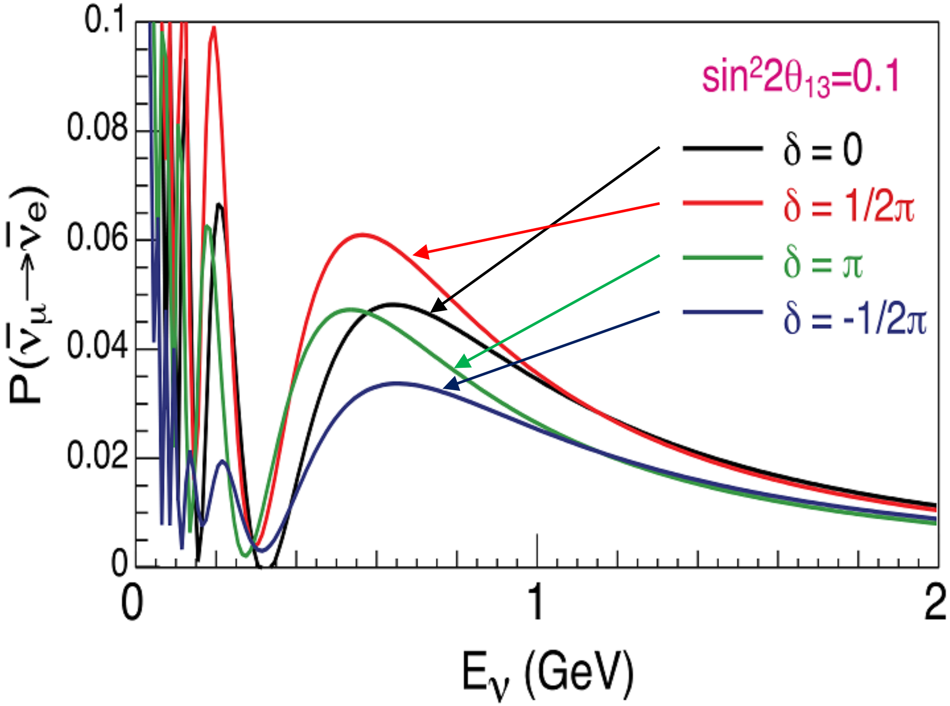
$\nu_\mu \rightarrow \nu_e$ probability (L=295km)

Normal hierarchy

Neutrino case



Anti-neutrino case



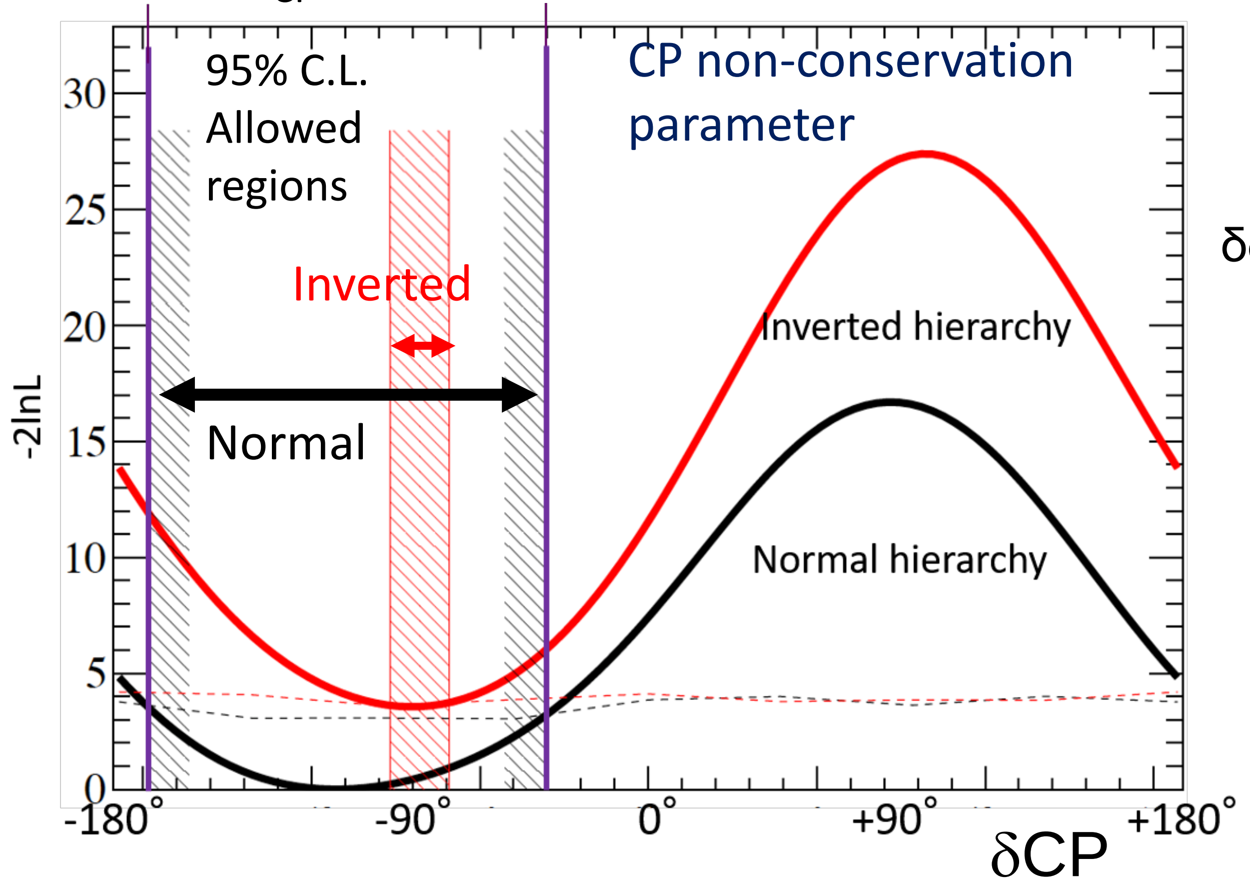
- Comparison between $P(\nu_\mu \rightarrow \nu_e)$ and $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
  - As large as ~25% from nominal

T2K: Results on δCP from $\nu_e + \bar{\nu}_e$ appearance

ν_μ 14.7x10^{20} POT $\bar{\nu}_\mu$ 7.5x10^{20} POT

ν_e Observed = 89, $\bar{\nu}_e$ Observed = 7

(in case of δ_{CP} = 0 67 9)



δ_{CP} = [-171°, -34°] (NH)
[-88°, -68°] (IH)
@95% CL

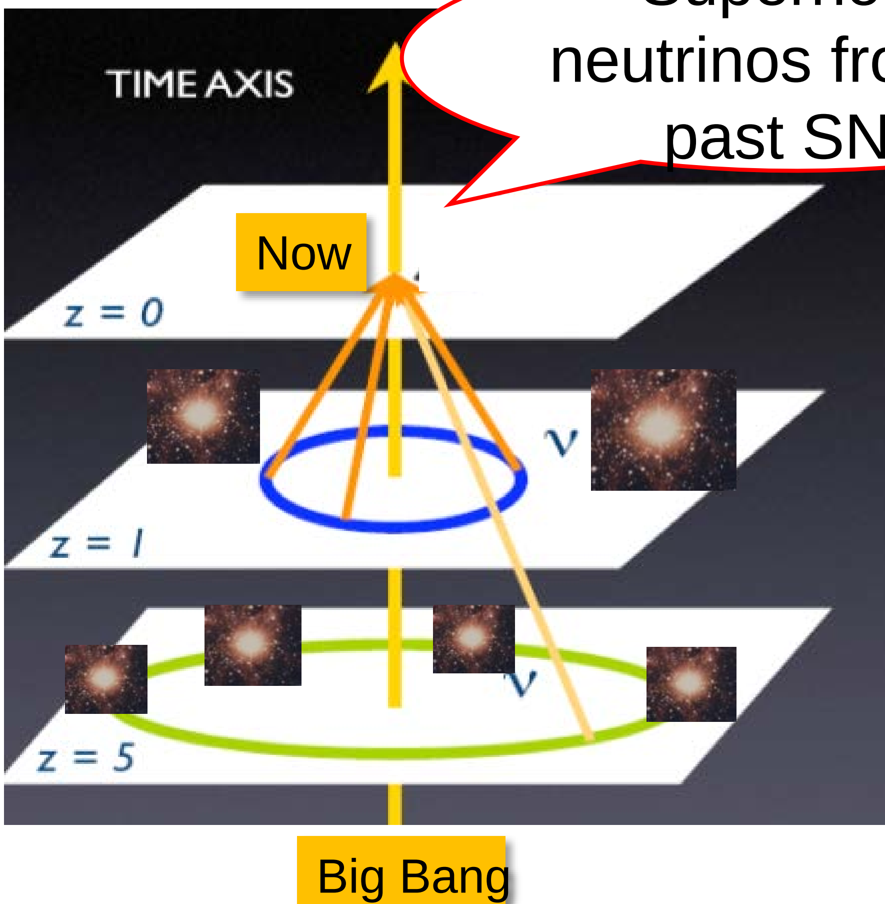
The best fit points lie near the maximally CP violating value δCP=-0.5π. The CP conserving values (δCP=0 and δCP= π) lying outside of the T2K 2σ confidence level interval.

Future of Super-K, and Hyper-K project

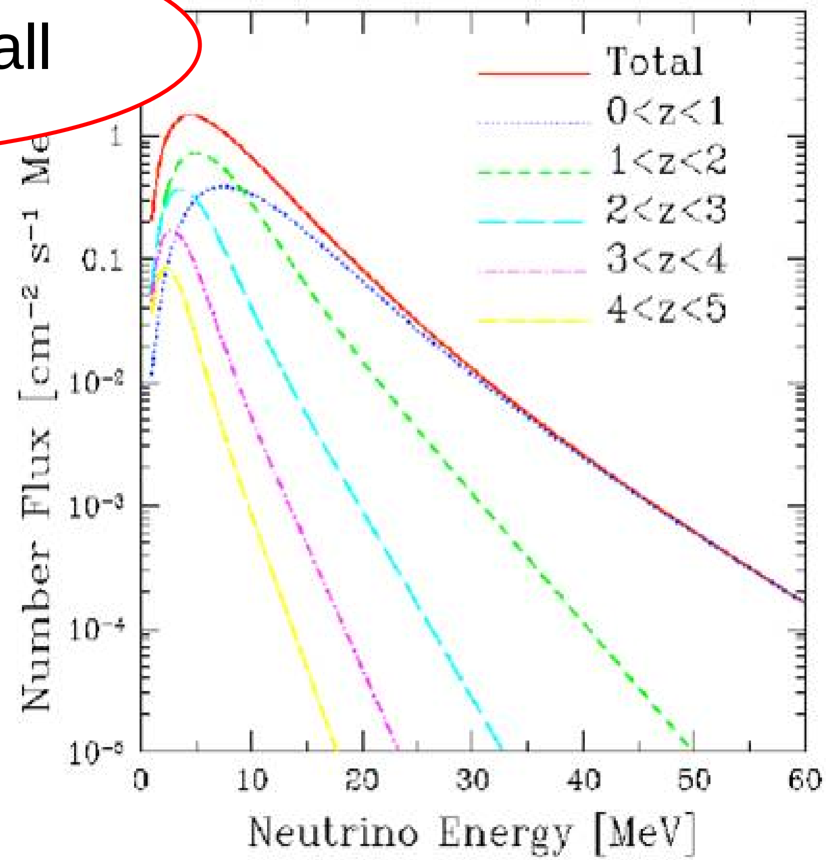
Supernova Relic Neutrinos

~10^{10} stars/galaxy × ~10^{10} galaxy × 0.3%(massive star->SN) ~$O(10^{17})$SNe

Supernova neutrinos from all past SNe

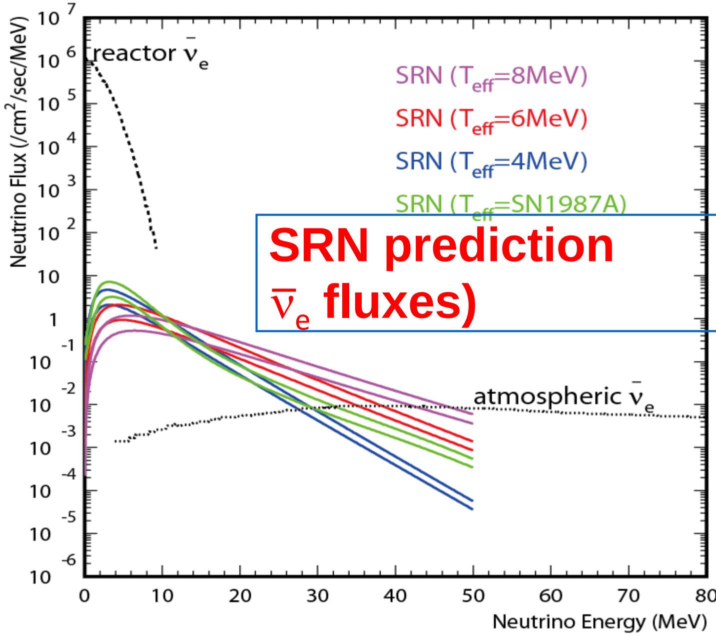


Expected energy spectrum

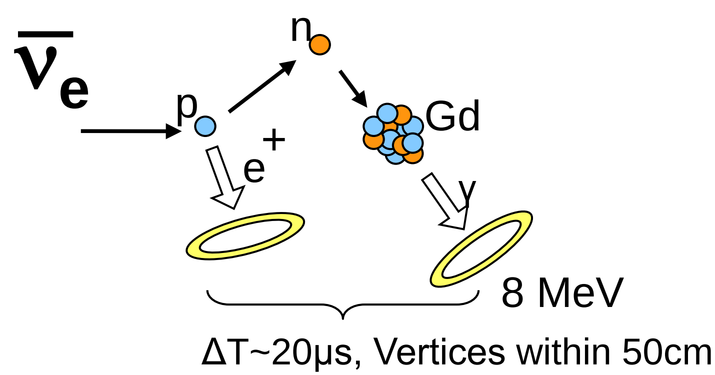


S.Ando, Astrophys.J. 607, 20(2004)

SK-Gd project for Supernova Relic Neutrino

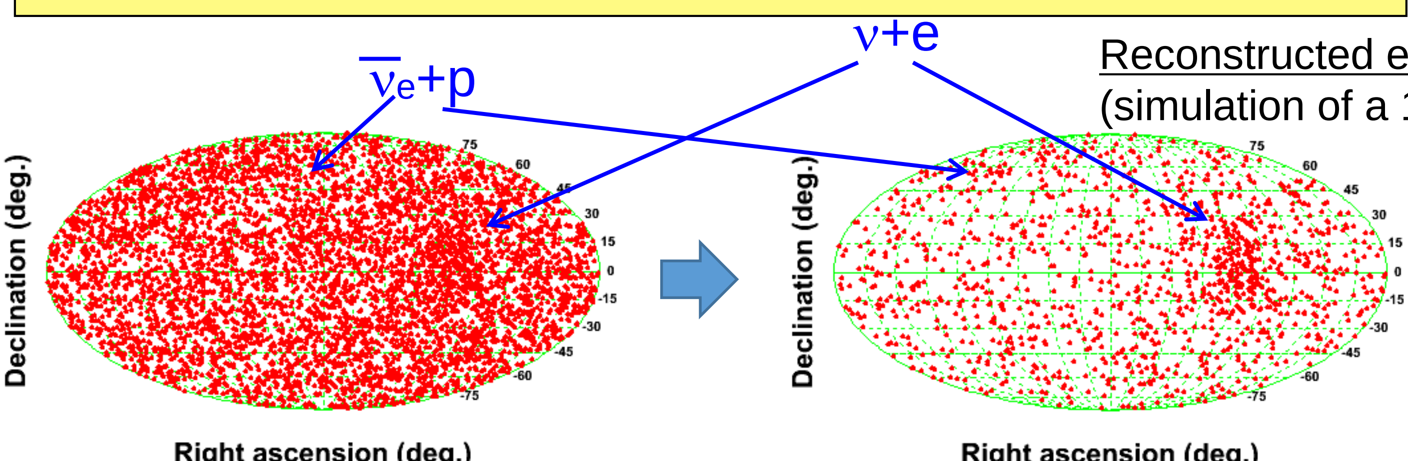


Open widow for SRN at 10-30MeV
Expected rate 1.3 -6.7 events/year/22.5kt(10-30MeV)



Identify $\bar{\nu}_e$+p events by neutron tagging with Gd.
90%(50%) capture efficiency with 0.1% (0.01%) Gd in water.

Improve pointing accuracy for galactic supernova bursts,
e.g. 4~5°→ 3°(90%C.L.) for 10kpc

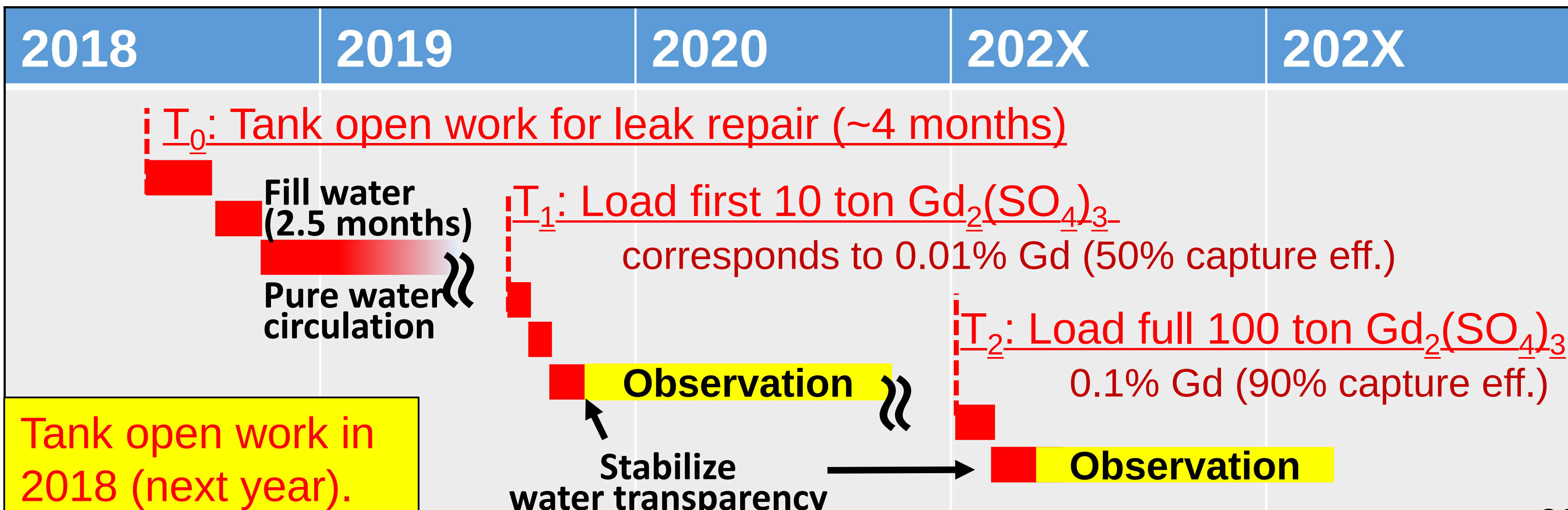


Reconstructed e^+/e^- direction
(simulation of a 10kpc supernova)

Preparation and plan for SK-Gd project

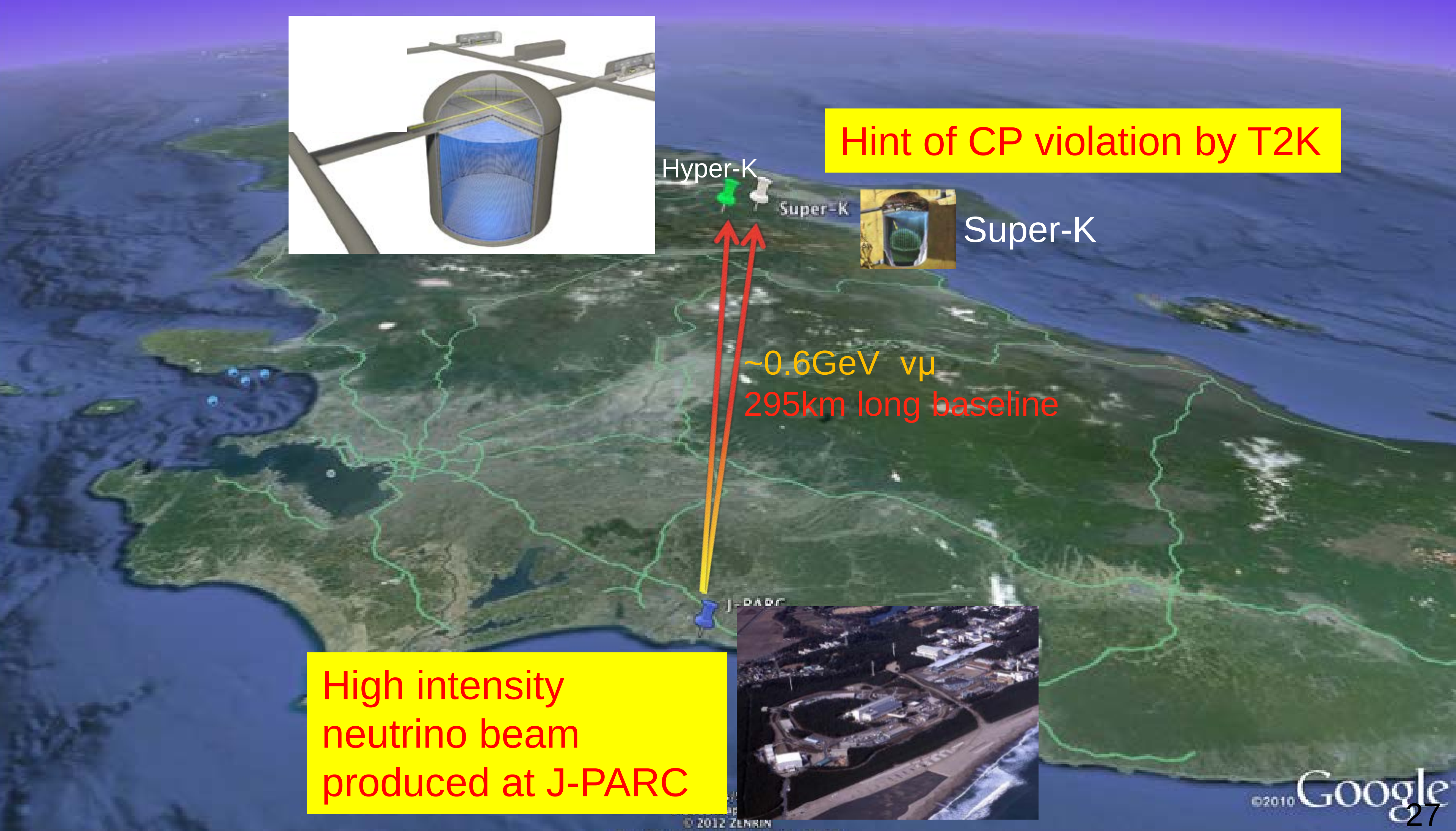
Gd-loading, pre-cleaning and Gd-water circulation systems were constructed.

Low radioactive $Gd_2(SO_4)_3$ power has been developed and getting close to our goals. Uranium and radium removal resins have been developed.



Neutrino oscillation vs. anti-neutrino oscillation

Evidence and precise measurement by Hyper-Kamiokande

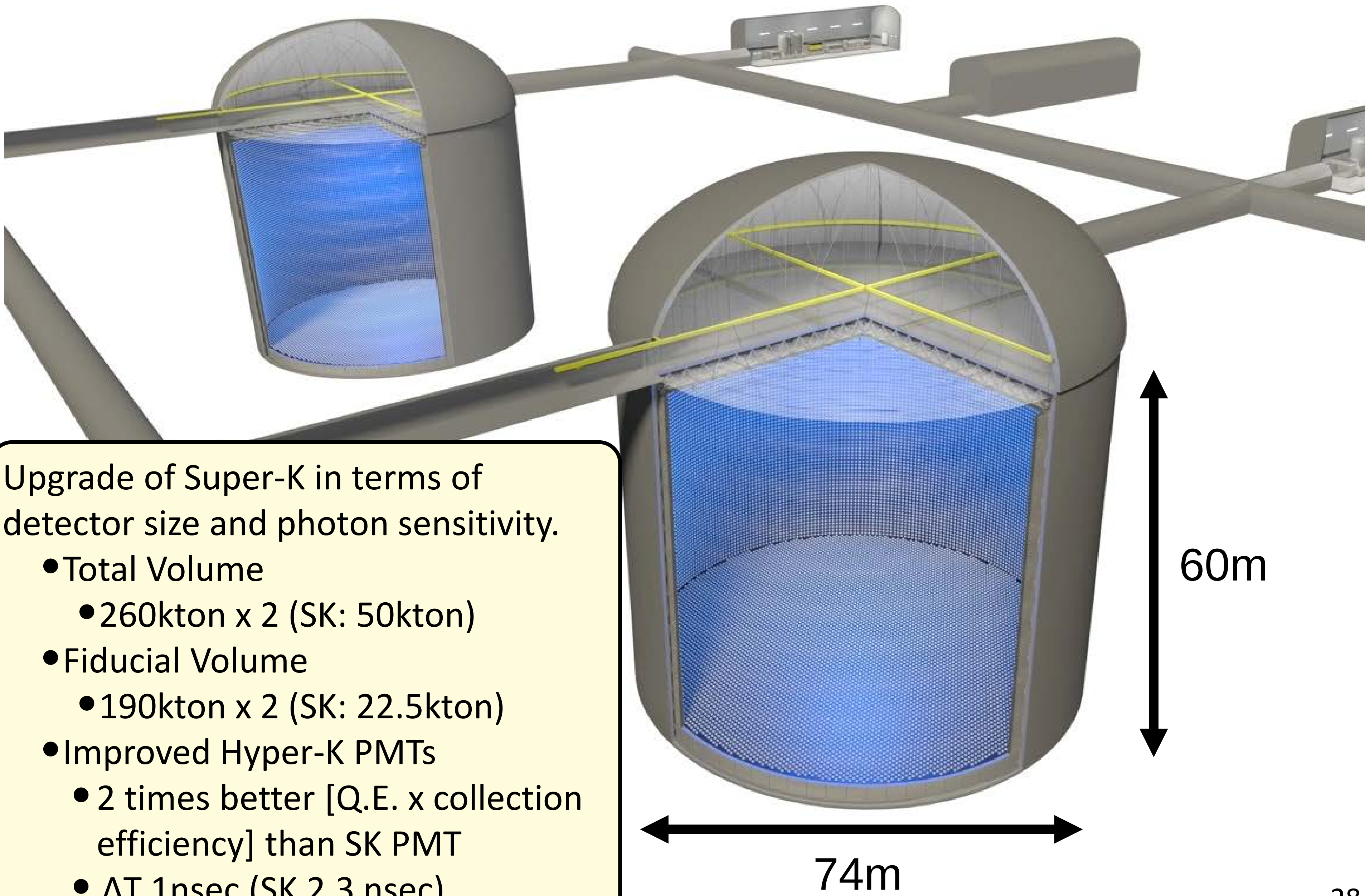


Hint of CP violation by T2K

Super-K

High intensity
neutrino beam
produced at J-PARC

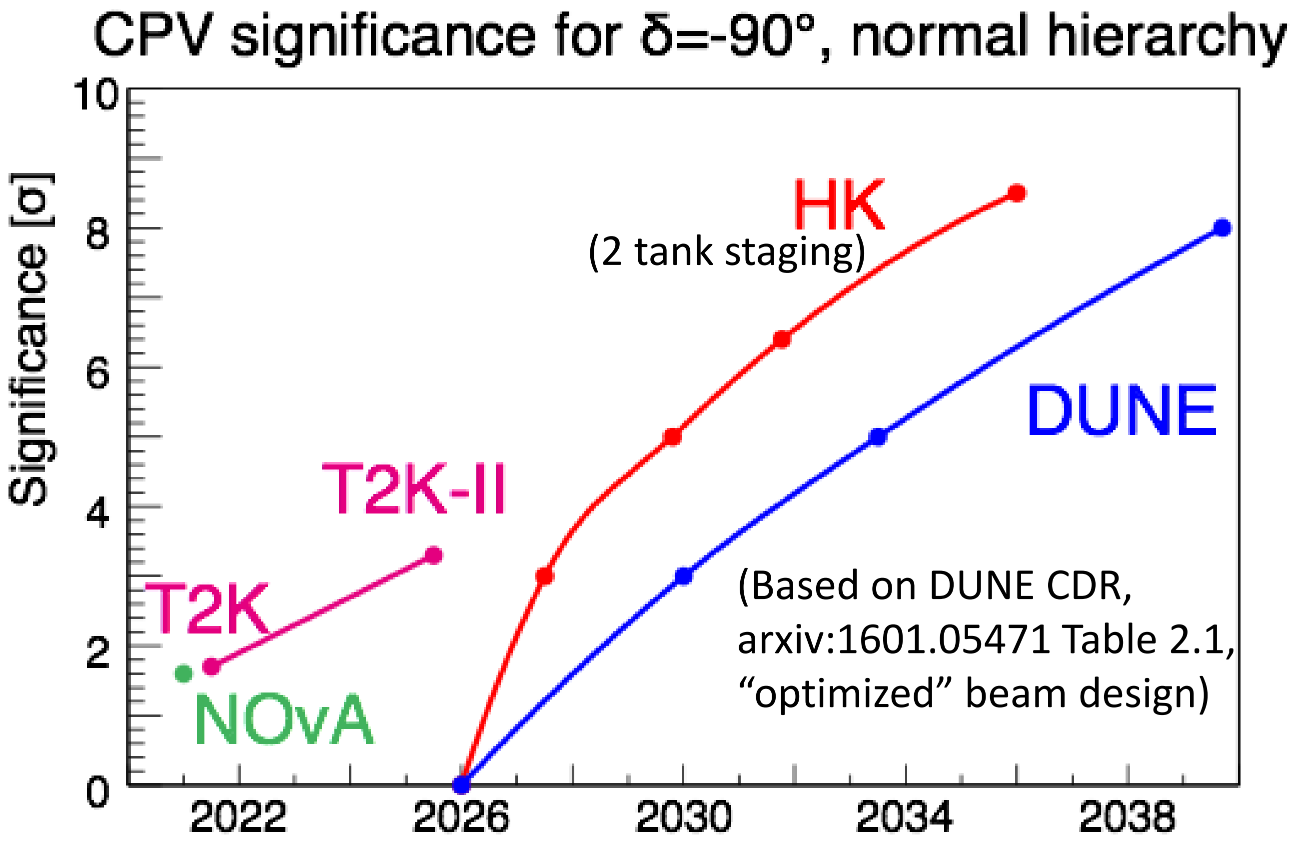
Hyper-Kamiokande



Upgrade of Super-K in terms of detector size and photon sensitivity.

- Total Volume
  - 260kton x 2 (SK: 50kton)
- Fiducial Volume
  - 190kton x 2 (SK: 22.5kton)
- Improved Hyper-K PMTs
  - 2 times better [Q.E. x collection efficiency] than SK PMT
  - ΔT 1nsec (SK 2.3 nsec)

Towards leptonic CP asymmetry



Strategy of Japan-based program

~3σ indication with T2K→T2K-II,

>5σ discovery and measurement with HK

A Multi-purpose Experiment

Comprehensive study of ν oscillation

- CPV
- Mass hierarchy with beam+atmosph. ν
- θ_{23} octant
- Test of exotic scenarios

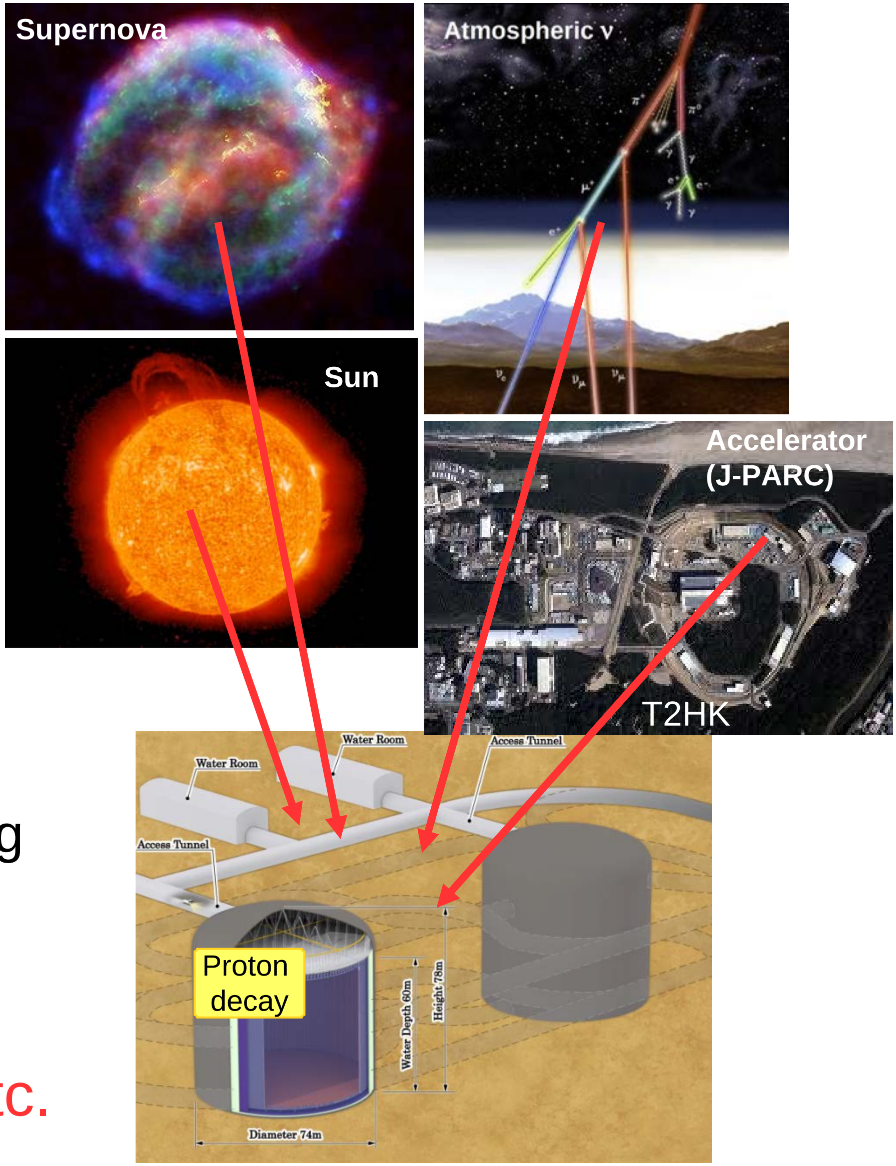
Nucleon decay discovery potential

- All visible modes including p → $e^{+} \pi^{0}$ and p→$\bar{\nu}K^{+}$ can be advanced beyond SK.
- Reaching 10^{35}yrs sensitivity

Unique Astrophysics

- Precision measurement of solar ν
- High statistics Supernova ν with pointing capability and energy info.
- Supernova relic ν (non-burst $\bar{\nu}$) observation is also possible

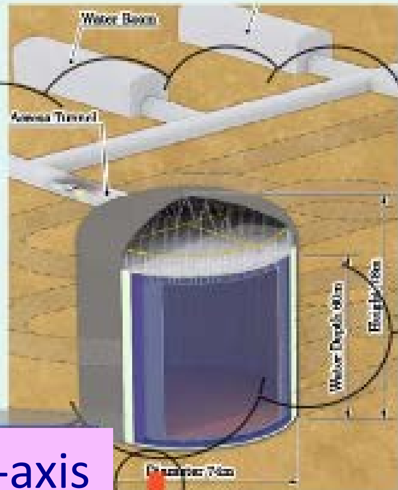
Earth core's chemical composition etc.



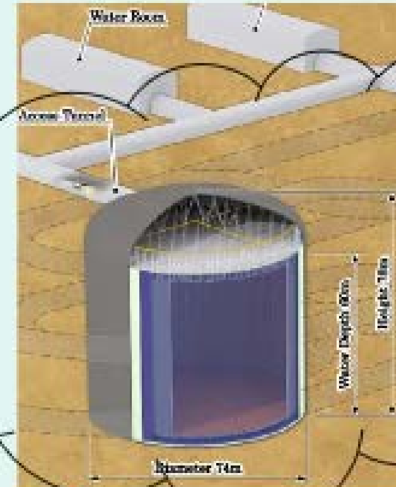
2nd Hyper-K Detector in Korea

T2HKK

KNO
Korean
Neutrino
Observatory



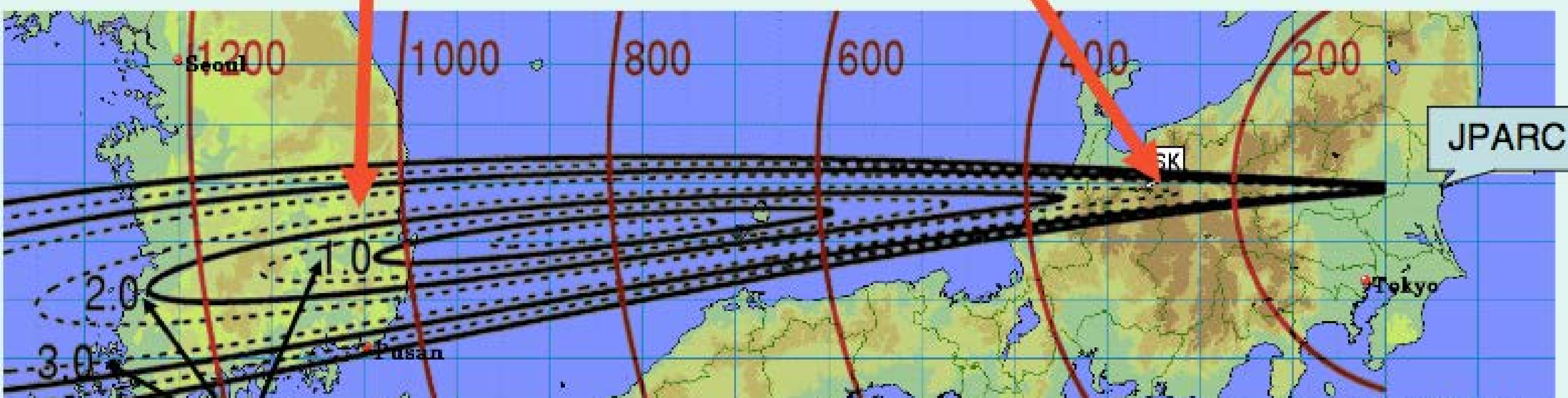
1~3 deg. off-axis



Hyper-K

2.5 deg. off axis

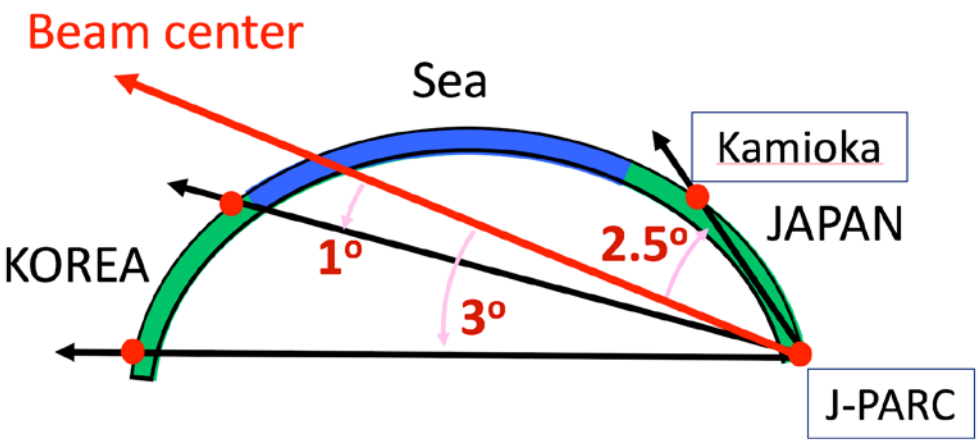
The J-PARC ν beam comes to Korea.

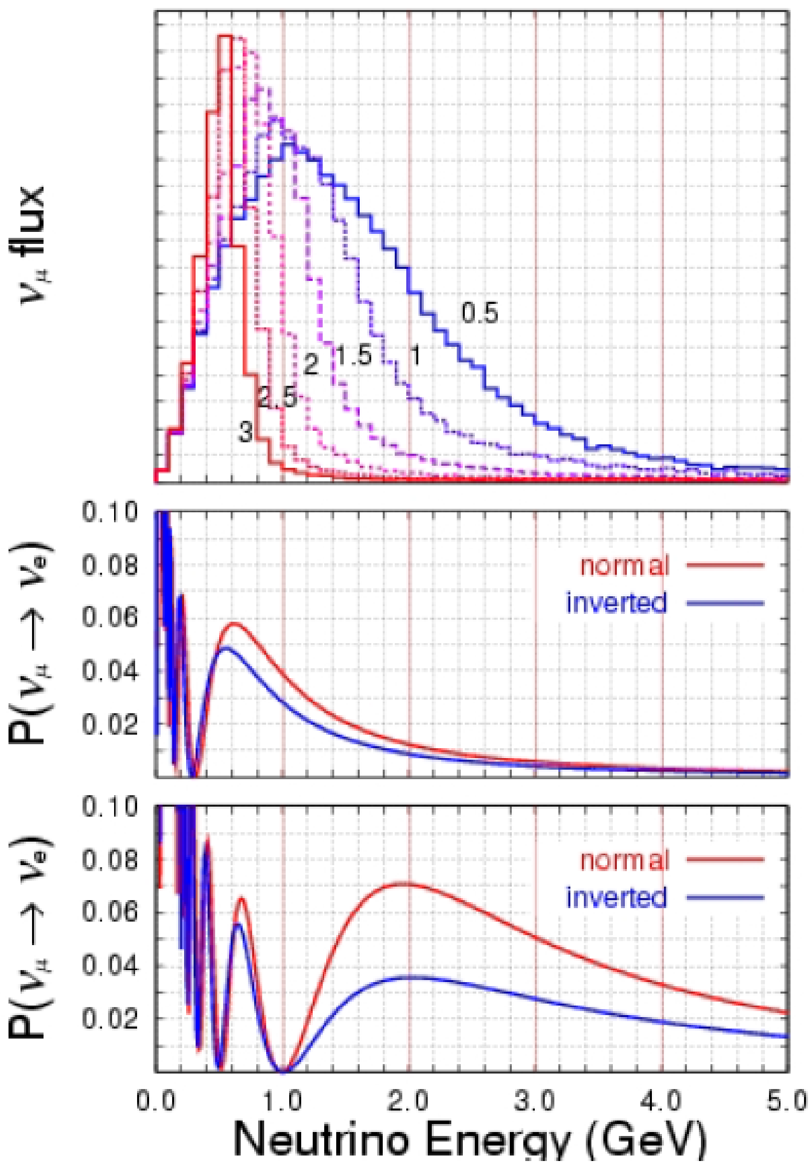


Off-axis angle

see hep-ph/0504061
By K. Hagiwara, N. Okamoura, K. Senda

Neutrino Oscillations in Kamioka & Korea





← Profile of off-axis beams

← $P(\nu_\mu \to \nu_e)$ at SK/HK (Japan)
(L = 295 km)

← $P(\nu_\mu \to \nu_e)$ at Korea
(L=1000km)

Benefits of T2HKK

T2HKK = **T**okai to(**2**) **HK** to **K**orea

- ❑ Physics programs: the same as the Hyper-K
- ❑ **Physics sensitivities improves** in the following topics

- ➢ Neutrino mass hierarchy determination
- ➢ Leptonic CP violation phase measurement

← **1st&2nd oscillation maxima**

- ➢ Non-standard neutrino interaction

← **Higher ν energy Longer baseline Higher matter density**

- ➢ Solar/SN/SRN/ν geo physics sensitivities

← **Deeper site: 650 vs. 1000 m**

T2HKK can serve as a neutrino telescope for > 30 years.

Conclusions

- More than 30 years have passed since we started experiments at Kamioka.
- Neutrino oscillations have been established in the last 30 years.
- There are still many important unknowns in neutrino physics.
- Future developments are expected.

Interesting future in neutrino physics!